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Hybrid marine power plants model validation with strategic loading

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Abstract: Recent advances in Energy Storage Devices (ESD) technology has enabled new supervisory control strategies for power generation and distribution on hybrid marine power plants, supported by new class society regulations. A marine hybrid power plant is characterized by the presence of both a traditional power producer, i.e. diesel Generator-set (genset), and an ESD, i.e. batteries. In this paper, two models to estimate strategic loading average fuel consumption were derived and compared. The first model is a higher fidelity dynamic model formulated as a hybrid system, in which the simplified engine dynamics is included, accounting for both continuous-time and discrete-time dynamics representing gensets and ESD as well as the switching. The second model consists of a steady state weighted average, where transient effects are not taken into account. Both models disregard thermal effects on the engine as well as assume that the engine fuel consumption is only a function of the engine speed and power output. The motivation to derive two models is due to the fact that the static model, due to its steady state nature, can estimate the expected weighted average fuel consumption very fast, being a new tool on the hybrid power plant operation optimization. The hybrid model, due to its dynamic nature and accounting for continuous-time and discrete-time dynamics, takes a longer time to simulate the system, which is unfeasible when it comes to real time operations. It is thus required to estimate the errors in the weighted average model due to the simplifications, asserting for which cases it is valid. The results show that the steady state model gives the exact solution in cases where dynamic effects are not relevant. It is a good approximation for systems where the switching period is much higher than the engine time constant, and the load dynamics time constant. The switching frequency is directly related to the ESD energy storage capacity, thus, systems with a large ESD will be better approximated by the steady state model than systems with relatively small ESD.

Keywords: Hybrid power plants in marine systems, Modeling, identification, simulation, and control of marine systems

NOTATION

The nomenclature with abbreviations and symbols used throughout this paper is presented in appendix A. The letter "$_C$" used as a subscript denotes the system while the ESD is being charged, while the subscript "$_D$" denotes the system while discharging the ESD. The subscript "$_0$" refers to the initial conditions. An over-line over a variable (e.g. "$\overline{F}$") denotes the time average of that variable. A dot above a variable (e.g. "$\dot{F}$") denotes its time derivative. The subscript "$_B$" is denotes that the variable is related to the ESD, the subscript "$_G$" is denotes that the variable is related to the generator, and the subscript "$_L$" is denotes that the variable is related to the load. The subscript "$_{max}$" denotes the maximum value that a variable can assume, while the subscript "$_{min}$" denotes the minimum value that a variable can assume

1. INTRODUCTION

Hybrid marine power plants may be a great solution for safer and greener energy management in marine vessels, reducing fuel consumption and emissions. In a hybrid power plant, the generators are assisted by the presence of ESDs. It presents a big potential to improve power plants safety and efficiency, since it can be used to reduce fuel consumption, emissions and/or power fluctuations.

Fig. 1 shows an example of a hybrid power plant single line diagram and it's most important components. More details about shipboard electrical power systems can be found in Patel (2011) and Kundur et al. (1994).

Hybridization is not a new concept, since it has been constantly studied in other areas such as the automotive industry. Rodatz et al. (2005) present the Power Manage-

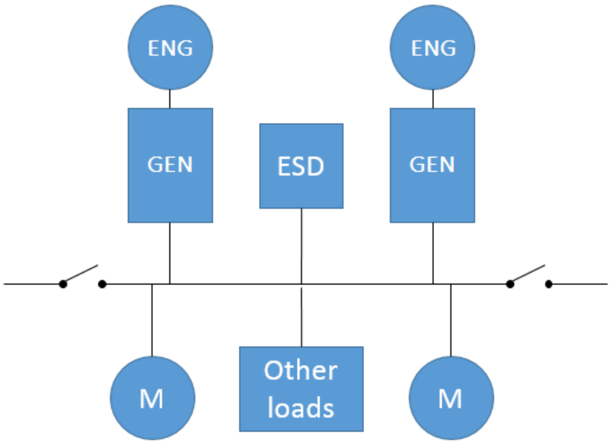

Fig. 1. Example of a hybrid power plant. *ENG* stands for engines, *G* stands for generators, and *M* stands for electric propulsion motors.

ment System (PMS) for a real car with a fuel cell/super capacitor hybrid power system, Sulaiman et al. (2015) review the Energy Management System (EMS) for hybrid vehicles, and Guo et al. (2015) show the effects of buses hybridization. The automotive industry is not the only area where hybridization has been used successfully, examples include household applications as shown in Nižetić et al. (2015), and cranes, lifts and tooling machines as described in Grbović et al. (2012) and Kim and Sul (2006).

Recent developments in ESD technology increased the energy density as well as its reliability, which lead to modification in class rules, shown in DNV-GL (2015), where ESD can be used instead of a generator. With the possibility to operate a hybrid marine power plant, it is then necessary to study the new operations that are enabled by the power plant hybridization. A comprehensive discussion of the different ESD technologies can be found in Chan (2007).

Several high level control systems were proposed to control the ESD, with different goals, where its main objective is to minimize fuel consumption, emissions, and / or maximize safety. The main control systems for ESD were explored in Lindtjørn et al. (2014). The most common ESD usage strategies are "Enhanced Dynamic Performance", "Peak Shaving", "Spinning reserve", "Strategic loading", and "Zero Emissions Operation".

The main contribution in this paper is to model mathematically and validate the interaction between the diesel genset and the ESD. Two approaches are used to model the hybrid marine power plant. The hybrid model is a higher fidelity approach, with dynamic effects taken into consideration, where the steady state model disregards all transients. The higher fidelity model is used as a benchmark to measure the weighted average model results. It is important to show the validity range for both models and discuss the implications of the effects that were not modeled.

It is important to highlight that the term "hybrid" is used in two different scenarios in this paper. The first one refers to the "hybrid" power plant, where an ESD is added to a conventional marine power plant. The second usage is refering to the "hybrid" models, where it consists of a dynamical system with both continuous-time and discrete-time behavior. It should be clear to which denotation is used in each case.

Section 2 describes in details hybrid marine power plants, section 3 introduces and explains the strategic loading, section 4 derives the hybrid model, section 5 simplifies the hybrid model, calculating the weighted average static solution, the results are presented in section 6, and section 7 presents the conclusions found in this study.

2. HYBRID POWER PLANT

A marine power plant consists of generators (usually driven by diesel or gas), frequency converters, transformers, and motors connected to the power bus. A hybrid power plant differs from a conventional power plant due to the presence of one or more ESD (usually batteries or ultra-capacitors).

A mathematical model for a simple hybrid power plant is developed. It is assumed that the only losses present in the system are due to the ESD charge/discharge cycle. Since no transmission and associated power electronics losses are considered, the power produced by the generator (P_G) and the power injected in the system by the ESD (P_B) equals to the demanded power from the load (P_L), such that:

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

It will be assumed that the load demanded power is an input to the system, varying dynamically depending on the various enabled power consumers, operational profile as well as the environmental conditions. The ESD power output will be controlled using the set-point generator defined as "strategic loading".

A block diagram of the main components of the hybrid power plant can be seen in fig. 2. The strategic loading, which will be described in more details in section 3, has the load demanded power as input, and it generates setpoints for the ESD.

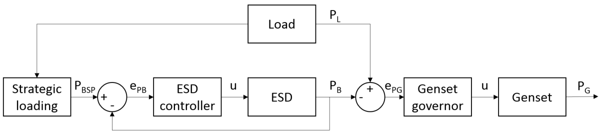

Fig. 2. Strategic loading hybrid power plant block diagram.

2.1 *Generator-set (genset)*

Gensets consist of one engine and one generator. The engine could use any type of fuel, but the most common for marine application are diesel and gas engines.

The generator converts torque from the engine into electricity. The output could be AC or DC. Most marine applications use AC grids, thus, the engine usually operates in a fixed frequency. In cases where the grid frequency is not fixed (either DC grids or AC with frequency converters after the generator), the engine has more flexibility to operate in an area with a better fuel efficiency.

The most important characteristic from the genset is the Fuel Oil Consumption (FOC) curve, which can be modeled as a dynamical function of the load (P_L), changes in the load ($\dot{P}_L$), engine speed (ω), and temperature (T):

$$FOC(t) = f(P_L, \dot{P}_L, \omega, T) \tag{2}$$

Instead of the FOC curve, it is usual to find the engine Specific Fuel Oil Consumption (SFOC) curve, which can be converted by:

$$FOC = SFOC \cdot P_G \tag{3}$$

The mechanical system time constant is much slower than the electrical system. The engine will be assumed to behave as a first order system with time constant τ_G. The engine governor (low level controller) is assumed to be an ideal controller and will not be considered, since the engine will always converge for the desired set-point.

The engine FOC curve was found experimentally using the diesel engine Perkins 2506C-E15TAG1 retrofitted with a CAT C15 controller in the hybrid marine power laboratory at NTNU. It is noteworthy that the measurements may include deviation due to the sensors used and will vary for each engine. The SFOC curve for this specific engine is shown in Fig. 3.

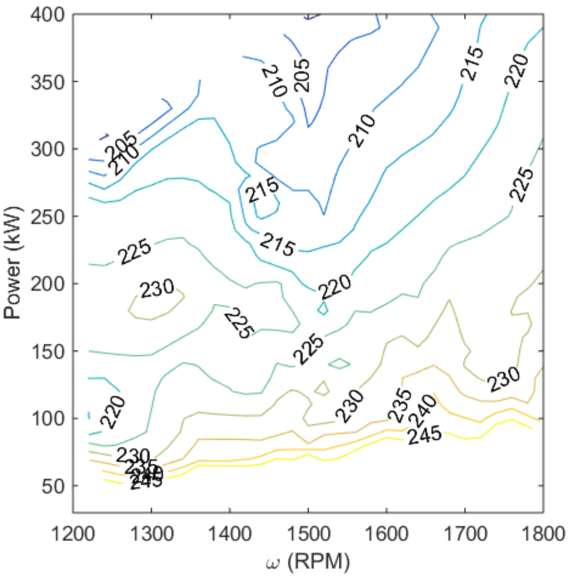

Fig. 3. Perkins 2506C-E15TAG1 Specific Fuel Oil Consumption (in g/kWh), NTNU hybrid laboratory.

2.2 Energy Storage Devices

An ESD is a component in the power bus that is able to absorb or provide power to the grid. The main examples of ESD are batteries, ultra-capacitors and flywheels.

Regardless of the technology that is being used, some parameters are common for each technology: The maximum rated charge and discharge power (Δ_{Cmax} and Δ_{Dmax} respectively), charging and discharging efficiency (η_C and η_D respectively), and maximum energy capacity (E_{max}).

It is assumed that the ESD local controller is able to follow the set-points. The ESD time constant is much faster than the mechanical system time constant. Due to those two assumptions, the ESD controller is assumed ideal.

It is expected from the ESD that it lasts for an average of 10 years. As an example, batteries are expected to last for more than 2.000 charge/discharge cycles, such as in Super-B (2016), which would mean that if the strategic loading is used constantly for the 10-year period, one charge/discharge cycle should last for approximately 44 hours. The exact number of charge/discharge cycles will depend on the ESD size and technology, ranging from a few hundred to over 100.000 cycles. In this paper, it will be assumed that the charge/discharge cycles are much faster, which would be an extreme case.

3. STRATEGIC LOADING

Strategic loading consists of charging the ESD for a period of time τ_C and discharging it for a period of time τ_D with charge/discharge power Δ_C and Δ_D respectively. It is necessary that the energy balance in the ESD is constant after one charge/discharge cycle, such that:

$$E_C = \int_0^{\tau_C} \Delta_C(t) \cdot \eta_C(t) dt \tag{4a}$$

$$E_D = \int_0^{\tau_D} \frac{\Delta_D(t)}{\eta_D(t)} dt \tag{4b}$$

$$E_C = E_D \tag{4c}$$

E_C is the energy charged to the ESD, E_D is the energy discharged from the ESD, $\eta_C \leq 1$ is the charging efficiency, and $\eta_D \leq 1$ is the discharging efficiency.

The charging time and discharging time will depend on the ESD properties, specially the maximum rated energy capacity. It is a good practice to not charge it completely nor discharge it completely, since the charging efficiency is lower at high State Of Charge (SOC) and having a low SOC may damage permanently the ESD. The ESD will be charged until it reaches SOC_{max} and discharged until it reaches SOC_{min}. The state of charge can be modeled as:

$$SOC(t) = SOC_0 + \int_0^{\tau} \frac{P_B}{E_{max}} dt \tag{5}$$

We will define a state variable (s) which will identify if the system is in an ESD charging or discharging mode of operation. In this paper it will be assumed that $s = 0$ means that the ESD is discharging, and $s = 1$ means that it is charging.

A switching rule is that if $s = 0$ and $SOC \leq SOC_{min}$, then the system should start charging the ESD, as well as if $s = 1$ and $SOC \geq SOC_{max}$, it should start discharging.

The discrete variable s is the main reason why it is interesting to model the system with a hybrid framework (Goebel et al. (2012)), since all the states are continuous except for s.

The diesel engine is modeled to calculate the estimated fuel consumption and the average fuel consumption. By disregarding the temperature effects, it is known that at any time instant the SFOC and FOC tables are given:

$$F = FOC(P_G, \omega) = P_G \cdot SFOC(P_G, \omega) \tag{6}$$

The average fuel consumption and its derivative, for a given simulation time (τ), are calculated as:

$$\overline{F} = \frac{1}{\tau}\int_0^{\tau} F dt \tag{7a}$$

$$\dot{\overline{F}}(\tau) = \frac{F(\tau) - \overline{F}(\tau)}{\tau} \tag{7b}$$

$$\overline{F}(0) = F(P_G(0)) \tag{7c}$$

Due to the engine FOC curve, $\overline{F}$ might be different from $FOC(P_L)$, since the FOC curve is not linear. The shape of the FOC curve is the main deciding factor of the strategic loading parameters. If P_L is in a concave region, $\overline{F} < FOC(P_L)$. If P_L is in a convex region, $\overline{F} > FOC(P_L)$.

4. HYBRID MODELING

It is common to distinguish continuous-time systems from discrete-time systems. The hybrid framework combines both methodologies, assuming that a system has a behavior that is characterized by a continuous-time model as well as discrete-time behavior. The way that the simulation evolves can be seen in Fig. 4, where t is the continuous-time and the number of jumps (number of times that the system has a switching behavior) is j.

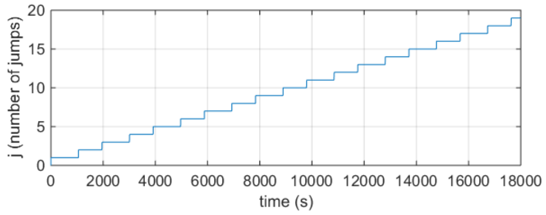

Fig. 4. Representation of the hybrid time t and j

The hybrid system has both continuous-time dynamics and discrete-time dynamics. The continuous-time dynamics (flows) is responsible for the generator speed, load demanded power, etc. The discrete dynamics (jumps) defines the ESD dynamics, when its set-point is switched instantly to a new value, consequently, altering the generator produced power as well. This hybrid model ($\mathcal{H}$) is defined in Goebel et al. (2012), according to:

$$\mathcal{H} = (C, F, D, G) \tag{8}$$

And the state varies according to:

$$x \in C \quad \dot{x} \in F(x) \tag{9a}$$

$$x \in D \quad x^{+} \in G(x) \tag{9b}$$

C is the flow set, F is the flow map, D is the jump set, and G is the jump map. Both flow and jump sets define the region where the system is flowing or jumping, respectively, while the flow and jump maps define the system behavior inside the respective sets. A well posed system described by (9) can be analyzed for stability according to the framework proposed in (8) and (9).

The hybrid system needs to define several states to properly model the hybrid power plant, such as the generator produced power, the ESD produced power, the demanded load, the ESD state (s), the ESD SOC, the generator instantaneous frequency (ω), the simulation time (τ), the instantaneous fuel consumption, and the average fuel consumption (F and $\overline{F}$ respectively). All states are described by the state variable (x):

$$x = [P_G \; P_B \; P_L \; s \; SOC \; \omega \; \tau \; \overline{F} \; F]^T \tag{10}$$

Note that the generator speed is not assumed constant, so, transient effects are taken into account. This is to verify the simplified model with the higher fidelity hybrid model and verify the discrepancies between the full analysis and the weighted average static model. The initial conditions, given by the $_0$ subscript are given by:

$$x_0 = \begin{bmatrix} s_0 \cdot P_C + (1 - s_0) \cdot P_D \\ P_{L0} - P_{G0} \\ P_{L0} \\ s_0 \\ SOC_0 \\ \omega_0 \\ 0 \\ F_0 \\ F_0 \end{bmatrix} \tag{11}$$

The flow map is defined as:

$$f(x) = \dot{x} = \begin{bmatrix} (s \cdot P_C + (1 - s) \cdot P_D) - P_G \\ \dot{P}_L - \dot{P}_G \\ \dot{P}_L \\ 0 \\ (s \cdot \eta_C + (1 - s)/\eta_D) \cdot P_B / E_{max} \\ [s \cdot \omega_C + (1 - s) \cdot \omega_D - \omega]/\tau_G \\ 1 \\ [F - \overline{F}]/\tau \\ \dot{f}_{FOC} \end{bmatrix} \tag{12}$$

$\dot{f}_{FOC}$ is the FOC function time derivative. The jump map is defined as:

$$g(x) = x^{+} = \begin{bmatrix} P_G \\ P_L - P_G \\ P_L \\ 1 - s \\ SOC \\ \omega \\ \tau \\ \overline{F} \\ f_{FOC} \end{bmatrix} \tag{13}$$

f_{FOC} is the FOC value, given the parameters P_G and ω. The flow set is defined as:

$$C = C_1 \cup C_2 \tag{14a}$$

$$C_1 = (s = 0 \; \& \; SOC \geq SOC_{min}) \tag{14b}$$

$$C_2 = (s = 1 \; \& \; SOC \leq SOC_{max}) \tag{14c}$$

The jump set is defined as:

$$D = D_1 \cup D_2 \tag{15a}$$

$$D_1 = (s = 0 \;\&\; SOC \leq SOC_{min}) \tag{15b}$$

$$D_2 = (s = 1 \;\&\; SOC \geq SOC_{max}) \tag{15c}$$

5. WEIGHTED AVERAGE STATIC MODEL

A simplified model is derived, denoted as weighted average static model, where transient effects are disregarded. It means that the fuel consumption variation due to dynamic effects are not considered, and the engine is assumed to be capable of reaching the desired set-point on demand. This assumption is based on the fact that the loads tend to vary slowly in marine systems, as well as the presence of other ESD to perform peak shaving, the presence of EMS controlling the loads, etc. Finally, it is necessary that the time spent charging and discharging the ESD is much higher than the engine time constant.

Given (7a) and assuming that P_G during a charge cycle (P_C) and a discharge cycle (P_D), then it is possible to calculate the average fuel consumption as:

$$\begin{aligned}\overline{F} &= \frac{\int_0^{\tau_C+\tau_D} P_G \cdot SFOC(P_G, \omega)dt}{\tau_C + \tau_D}\\ &= \frac{\int_0^{\tau_C} P_C \cdot SFOC(P_C, \omega_C)dt}{\tau_C + \tau_D}\\ &+ \frac{\int_{\tau_C}^{\tau_C+\tau_D} P_D \cdot SFOC(P_D, \omega_D)dt}{\tau_C + \tau_D}\end{aligned} \tag{16}$$

The energy balance shown in (4) is simplified such that

$$\tau_C \cdot \Delta_C \cdot \eta_C = \frac{\tau_D \cdot \Delta_D}{\eta_D} \tag{17}$$

Combining (16) and (17), it is possible to derive:

$$\overline{F} = \frac{FOC(P_C, \omega_C) \cdot \Delta_D + FOC(P_D, \omega_D) \cdot \Delta_C \cdot \eta_C \cdot \eta_D}{\Delta_D + \Delta_C \cdot \eta_C \cdot \eta_D} \tag{18}$$

It is important to note that (18) does not take time into consideration, so, the ESD capacity does not affect $\overline{F}$.

6. SIMULATION RESULTS

Five simulation cases were run. The goal of each simulation is to isolate specific factors that might influence the accuracy of the weighted average model:

- Sim 1 presents the main inputs and outputs.
- Sim 2 analyzes the effects of the ESD efficiency.
- Sim 3 analyzes the effects of the ESD capacity.
- Sim 4 analyzes the effects of the genset dynamics.
- Sim 5 analyzes the effects of variable speed gensets.

Table 1 summarizes the simulation parameters:

Table 1. Simulations configuration

Variable	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5
P_L (kW)	50	190	190	190	190
P_C (kW)	80	350	250	250	250
P_D (kW)	40	80	80	80	80
$\eta_C \cdot \eta_D$ (%)	100	Var	90	90	90
$\omega(RPM)$	1500	1500	1500	1500	Var
E_{max} (kWh)	18	60	Var	Var	Var
$\tau_L(s)$	0	0	0	15	15

The constants of all simulations are shown in table 2:

Table 2. Simulations initial conditions

Variable	s_0	SOC_0	SOC_{min}	SOC_{max}	ω_0 (RPM)
Initial value	0	80%	20%	80%	1500

It is important to notice that the average fuel consumption should be be taken into account only at the end of each charging cycle, since the ESD starts with SOC_{max}, then the ESD starts injecting energy in the system. Thus, it is impossible to compare the system in cases where the SOC is not equal to SOC_0.

6.1 Simulation 1

The first simulation is a simple case where the engine dynamics are not taken into account. The engine produced power is shown in fig. 5, and both the instantaneous fuel consumption and its average are shown in fig. 6.

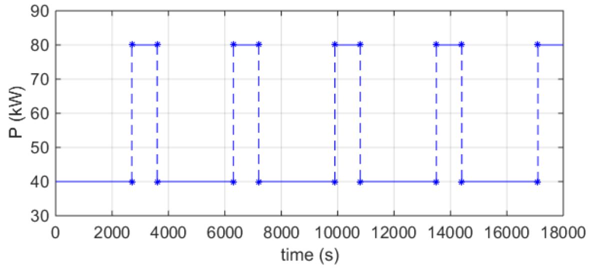

Fig. 5. Engine output power for the simulation 1

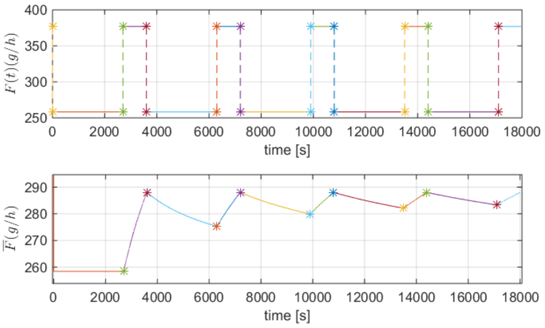

Fig. 6. F (upper) and $\overline{F}$ (lower) for the system with the ESD performing strategic loading for simulation 1

It is shown that $\overline{F}$ converges to 288.0 g/h. By using the weighted average static model (18) with the values shown in table 1, the same value of 288.0 g/h is found. Since all dynamic effects were disregarded, it was expected that both models have the same value. According to fig. 3, the fuel consumption for this P_L is 298.7 g/h, hence, by utilizing the strategic loading, the average fuel consumption is reduced by 3.58 %. The results are summarized in table 3.

Table 3. Simulations 1 results

Without ESD	Static model	Hybrid model	Models difference	Fuel Saving
298.7	288.0	288.0	0 %	3.58 %

6.2 Simulation 2

The second simulation shows the effect that the ESD efficiency has on the model as well as on the average FOC.

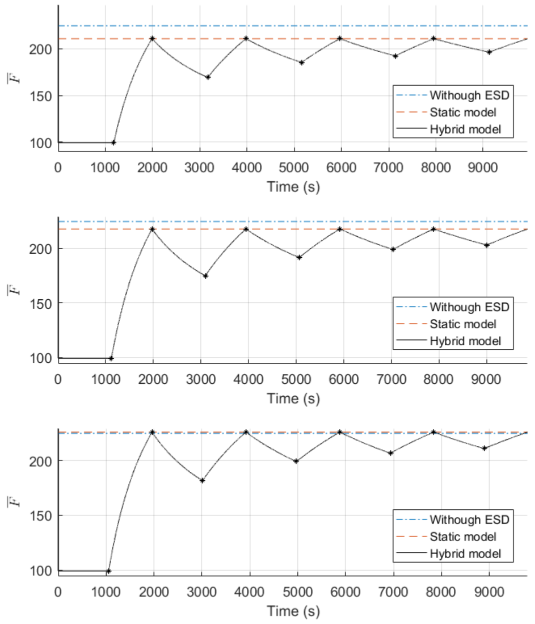

Fig. 7. $\overline{F}$ for the system without the ESD, the weighted average model and hybrid model for simulation 2. In the upper figure, the ESD efficiency is $\eta = 100\%$, in the middle figure, the efficiency is $\eta = 90\%$, and in the lower figure the efficiency is $\eta = 80\%$.

Table 4 summarizes the results from the simulated cases. The efficiencies in cases 1 to 3 are 100%, 90%, and 80%.

Table 4. Simulations 2 results

$\eta(\%)$	Without ESD	Static model	Hybrid model	Models difference	Fuel Saving
100	224.7	210.8	210.8	0 %	6.18 %
90	224.7	217.9	217.9	0 %	3.05 %
80	224.7	225.8	225.8	0 %	-0.50 %

The main result from this simulation is the fact that the hybrid model and the weighted average static model have the same result, as shown in Fig. 7, by the end of each charging cycle, the average fuel consumption is exactly the same as the weighted average static model.

Also, with a lower ESD efficiency, the fuel saving potential is lowered, even to the point where more fuel is consumed by having a low efficiency ESD in the system.

The efficiency will direct influence the design cycle, since a higher η usually leads to more fuel savings. Typical values for a lithium ESD ranges between 90% to 95%, whereas Compressed Air Energy Storage (CAES) tends have η around 70%.

6.3 Simulation 3

The ESD capacity will have a direct impact on the time that it takes for one charge/discharge cycle. The effect on the average fuel consumption is analyzed. The simulations shown in Fig. 8 are for cases with $E_{max} = 60kWh$, $E_{max} = 6kWh$ and $E_{max} = 0.6kWh$ respectively.

It is important to outline the fact that smaller ESD usually have a smaller maximum charge/discharge rates, but for the sake of simplicity, the limitations are ignored in this study. In real applications, depending on the ESD technology, it is necessary to impose limits to Δ_C and Δ_D.

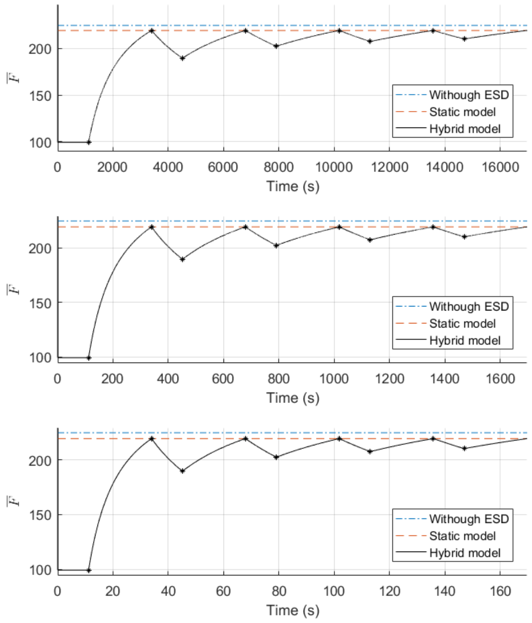

Fig. 8. $\overline{F}$ for the system without the ESD, the weighted average model and hybrid model. In the upper figure, the ESD capacity is $E_{max} = 60kWh$, in the middle figure, the capacity is $E_{max} = 6kWh$, and in the lower figure the capacity is $E_{max} = 0.6kWh$.

It is clear that the ESD dimension does not change the average fuel consumption overall dynamics, only changes the time scale. The time that the system takes to perform one charge/discharge cycle is directly proportional to E_{max}. The results are summarized in table 5.

Table 5. Simulations 3 results

E_{max}	Without ESD	Static model	Hybrid model	Models difference	Fuel Saving
$60kWh$	224.7	219.3	219.3	0 %	2.39 %
$6kWh$	224.7	219.3	219.3	0 %	2.39 %
$0.6kWh$	224.7	219.3	219.3	0 %	2.39 %

As expected, the steady state model and the hybrid model presents the same result for every simulated case. This is due to the fact that this simulation does not consider effects not modeled by the steady state model.

6.4 Simulation 4

Knowing that the load applied to the engine won't be an ideal step, the system is analyzed for cases where the load step is a first order system with time constant $\tau_L = 15s$. The effect of the ESD capacity is studied in this simulation.

Three ESD capacities are analyzed, being $E_{max} = 60kWh$, $E_{max} = 600Wh$, and $E_{max} = 60kWh$. The results are summarized in table 6.

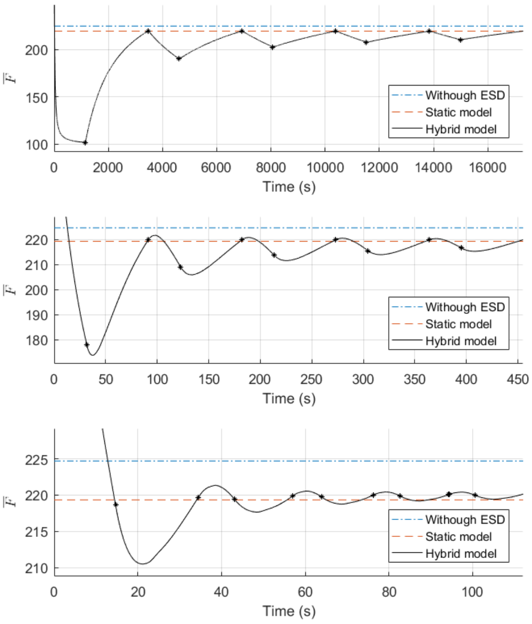

Fig. 9. $\overline{F}$ for the system without the ESD, the weighted average model and hybrid model for simulation 4.In the upper figure, the ESD capacity is $E_{max} = 60kWh$, in the middle figure, the capacity is $E_{max} = 0.6kWh$, and in the lower figure the capacity is $E_{max} = 6Wh$.

It is noticeable that the $\overline{F}$ over time is distorted by the dynamic effects. The generator loading dynamic makes the charge/discharge cycle take a longer time, as well as slowly varying the engine instantaneous fuel consumption. If there is any area between the engine load set-points, it will lead to an increase in $\overline{F}$.

Table 6. Simulations 4 results

E_{max}	Without ESD	Static model	Hybrid model	Models difference	Fuel Saving
$60kWh$	224.7	219.3	219.3	0 %	2.39 %
$0.6kWh$	224.7	219.3	219.3	0.28 %	2.11 %
$6Wh$	224.7	219.3	220.5	0.53 %	1.88 %

Even with the dynamic effects altering the system dynamics, it is shown that the average fuel consumption estimation from the hybrid model and the weighted average static model are similar, with a difference of 0.53% in the worst case scenario. The case with a 6 Wh has a charge/discharge cycle of around $16s$, being an unrealistic operation. Even with this unrealistic operation, the steady state model is a good approximation of the real system.

6.5 Simulation 5

Finally, the last case analyzed also takes into consideration the engine speed variation. The engine time constant is $\tau_G = 15s$, and $\tau_L = 15s$. The results are shown in Fig. 10.

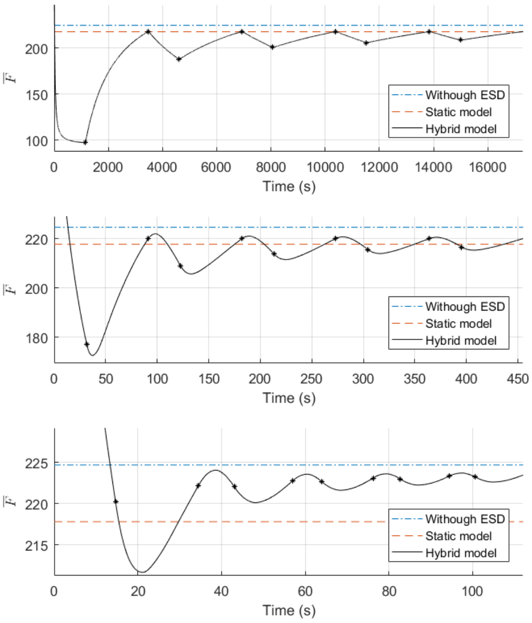

Fig. 10. $\overline{F}$ for the system without the ESD, the weighted average model and hybrid model for simulation 5. In the upper figure, the ESD capacity is $E_{max} = 60kWh$, in the middle figure, the capacity is $E_{max} = 0.6kWh$, and in the lower figure the capacity is $E_{max} = 6Wh$.

The difference between this case and case 6.4 is that the engine might operate in condition that is sub-optimal for the diesel engine, where the fuel consumption will be higher than the fixed frequency fuel consumption. This fact is shown in table 7, where the difference between both models is up to 2.9%. It is important to keep in mind that the case with the highest difference between the weighted average static model and the hybrid model is a case where the ESD has an inappropriate capacity for this operation. It is expected that the error due to dynamical effects will be irrelevant for real systems.

Table 7. Simulations 5 results

E_{max}	Without ESD	Static model	Hybrid model	Models difference	Fuel Saving
$60kWh$	224.7	217.8	217.9	0.03 %	3.04 %
$0.6kWh$	224.7	217.8	220.2	1.06 %	2.03 %
$6Wh$	224.7	217.8	224.3	2.90 %	0.18 %

7. CONCLUSIONS

In this paper, the difference between a higher fidelity hybrid dynamic model and a steady state model was studied. It was shown that for cases where dynamic effects are disregarded, such as engine dynamic response, load fluctuation, and engine load ramp, both models have the same result.

It was shown that the ESD efficiency will have a big influence on the resulting fuel consumption. On the other hand, the ESD capacity won't affect the system so much, since it will influence directly the time between switches (charge/discharge). However if the switching time is much larger than the engine time constant, the losses will be irrelevant.

The biggest effect on the fuel consumption is due to the ratio between the switching time and the engine/load time constant. This effect is even more pronounced in an engine with variable speed, since it can lead the engine to a operation where the fuel consumption is greatly increased.

The ESD life is related to the number of charge / discharge cycles. It is expected that the strategic loading cycle lasts longer than the mechanical system time constants, hence, the steady state model will approximate accurately the average fuel consumption for a well designed system with strategic loading.

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Appendix A. NOMENCLATURE

C	$= C_1 \cup C_2$, Hybrid system flow set.
C_1	Hybrid system flow subset.
C_2	Hybrid system flow subset.
$CAES$	Compressed Air Energy Storage.
D	$= D_1 \cup D_2$, Hybrid system jump set.
D_1	Hybrid system jump subset.
D_2	Hybrid system jump subset.
e	Error.
E	ESD energy.
E_{max}	ESD maximum energy rating.
EMS	Energy Management System.
ENG	Engine.
ESD	Energy Storage Devices.
f	function.
f_{SFOC}	SFOC curve.
F	Hybrid system flow map.
F	Fuel Oil Consumption.
FOC	Fuel Oil Consumption.
G	Hybrid system jump map.
GEN	Generator.
$Genset$	Generator-set.
$\mathcal{H}$	Hybrid system.
j	Discrete-time, number of jumps.
M	Motor.
P	Power.
PMS	Power Management System.
s	ESD state.
$SFOC$	Specific Fuel Oil Consumption.
SOC	State Of Charge.
t	Time.
T	Temperature.
x	Hybrid system states.
x^+	Hybrid system states discrete time step.
Δ	ESD input/output power.
η	$= \eta_C \cdot \eta_D$, ESD total efficiency.
τ	$= \tau_C + \tau_D$, Total cycle time.
τ_L	Load time constant.
ω	Engine angular speed.