An Energy Management Strategy for DC Hybrid Electric Propulsion System of Marine Vessels

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***Abstract* — Hybrid propulsion systems with DC distribution for marine applications are attracting interest due to the critical demands to reduce the fuel consumption and emissions of conventional marine vessels. To enhance the potential of these hybrid systems, it is essential to develop an energy management strategy (EMS) to distribute the required power properly between various components of the hybrid system. This paper therefore aims to develop an efficient EMS for DC hybrid electric marine vessels (HEMVs). The proposed EMS builds a set of operation rules which are based on the system states including power demands, engine states and battery performances to minimize the total consumed energy of the system and thus increase the power efficiency. The performance of the proposed EMS has been validated through numerical simulations.**

Keywords—energy management system; hybrid electric marine; hybrid propulsion system; marine vessel; DC grid.

I. Introduction

Emission reductions are the worldwide high priority efforts which aim at developing and employing either new technologies or feasible solutions to overcome environmental pollution aspects. Based on the report made by the International Maritime Organization (IMO) in 2014 [1], the CO_2 emissions are projected to increase up to 250% until 2050 while over 15% of the global NOx emissions come from the shipping industry. Meanwhile, the Paris convention set the global warming target to 2ºC. In addition, shipping is recognized as one of the most efficient transport means and is used to transmit goods in various industrial areas. Therefore, the operating profiles of ships have become increasingly diverse, especially for large size ships. As feasible solutions, the high emission level and low power efficiency of traditional ships whose power is supplied only by diesel generators (engine-driven) can be mitigated by properly using hybrid electric propulsion systems and advanced energy management systems.

Hybrid propulsion systems are developed based on the principles of combining electric propulsion systems with energy storage elements. Although electrical propulsion was introduced worldwide in the early of 1990s and offers key advantages over mechanical propulsion in terms of fuel economy, emissions and maintenance load, the HPS have been introduced globally through their applications in the automotive industry recently [2] and they are currently under investigation in the maritime industry [3]. A ship with energy storage system (ESS) can be identified as a special mobile and islanded micro-grid [4]. Large battery packs and super capacitors are considered as the most suitable options for the ESS technology development nowadays. In the literature, a lithium-ion battery pack combined with diesel generators has been investigated for ship crane operations [5]. In there, the complete auxiliary power system including diesel generators and a hybrid control strategy have been modelled and developed to reduce the minimal size and cost of battery pack for a hybrid ship. To minimize fuel consumption and reduce exhaust gas emissions, battery storage systems have been utilized to convert bulk carriers to all electric ships [6].

Although extensive research has been reported on efficient propulsion technologies and competency optimization of hybrid electric ships, the implementation of hybrid propulsion systems is generally limited to certain types of vessels and operating load profiles due to the complexity in the energy management and control. Therefore, the concerns for the HEMVs still remain of interest to researchers. The purpose of this paper is to develop an efficient EMS for a DC hybrid electric marine vessel which builds a set of operation rules based on the system states including power demands, engine states and battery performance to minimize the total consumed energy of the system while maintaining the system's performance.

This paper is then organized as: the representative architecture as well as main features of a generic HEMV are discussed for the design of the EMS in Section 2; Section 3 describes briefly the system modelling of key components; in Section 4, a rule-based controller (RBC) is designed for the EMS which relates to the system states such as diesel generator performance, power request based on the load profile, electric grid and battery status; test cases, numerical simulation and discussion are demonstrated to show the ability of the proposed EMS in Section 5; and finally, summary is concluded in Section 6.

II. DC Hybrid Electric Marine Vessels

A. *DC HEMV architecture: requirements and development*

The main requirements in designing a DC HEMV can be identified as follows:

- Maximize the system performance according to the operating load profile by optimizing the use of the electric propulsion system.

- Maximize the performance of the diesel engines-generators to improve the fuel saving and thus lower emissions.

- The speed of the diesel engines-generators can be varied since the DC power distribution does not lock the diesel engines-generators to operate at fixed speed, the engine speed can be optimized with respect to load profile.

To address these requirements, according to the key idea of hybrid propulsion systems in the automotive sector, an ESS of a generic DC HEMV is the combination of two or more power sources where the main power source comes from a set of generators driven by the diesel engines and another power source comes from a battery pack. The propulsion architecture of a DC HEMV can be presented in Figure 1. In this system, two diesel engines are used to drive DC generators which are used to generate electricity for the DC grid. The battery is selected properly and connected to the common DC distribution bus via a DC/DC converter. The total energy is then employed to drive the two propellers, thrusters and the auxiliary loads through power converters and electric transformers.

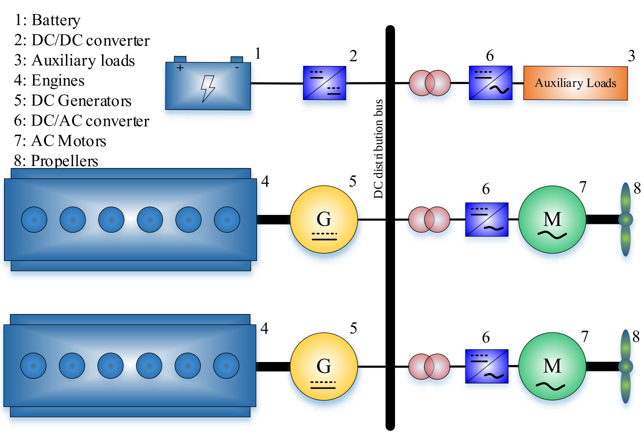

Figure 1. DC HEMV architecture.

B. *DC hybrid electric marine vessel systems*

The proposed HEMV has a hybrid power system where an energy storage device is usually used to increase the performance of the diesel engine-generators for the reduction of fuel consumption, and to maintain the performance of the system to follow the load profiles. Each diesel engine provides an optimal operation line (OOL), at which the best fuel economy can be achieved. In fact, the external load demanded on the DC bus will typically not allow the engine to run at its optimum region during the operation. Therefore, introducing the battery as another power source to the propulsion system can compensate the load dynamics and, consequently, helps the diesel engines to work in the high efficiency zones.

C. *Benefits and challenges of the utilization of battery pack in the DC HEMV*

As in the aforementioned discussions, the battery acts as the essential device in the DC HEMV. The proper utilization of the battery can bring the following benefits: The battery offers an additional direction to control and optimize the use of system power. The battery can provide electric power to drive the system where the engines can be turned off to avoid their low efficient working regions or when the required power of the engines is smaller than the available battery power. On the contrary, when the engine power is higher than the required power, the battery can be recharged by absorbing the excess power. In case of huge power request, the battery energy can be accumulated with the total energy from the diesel engines-generators to drive the system.

However, using the battery in the hybrid system still poses several challenges for the EMS which could make the controller complicated, such as: the EMS is required to decide the charging and discharging sequence of battery to minimize the fuel consumption and emissions of the diesel engine regarding the system performance. The control strategy is necessary to distribute properly dynamic loads between the engine and battery to minimize the load fluctuations due to the complexity of working load profiles. These challenges can be addressed in the following sections through the proposed system.

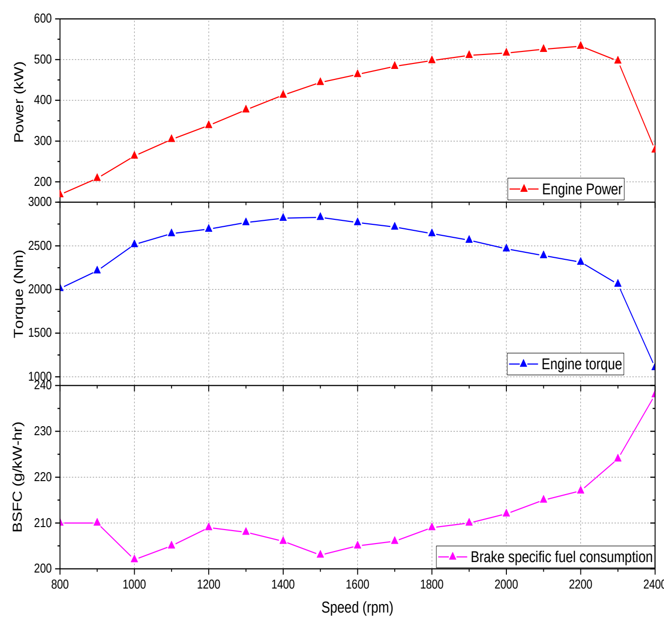

Figure 2. Diesel engine performance.

III. DC HEMV System Modelling

A. *DC hybrid electric marine vessel systems*

The diesel engine is simply represented based on the steady OOL of the Caterpillar engine where the maximum point of the performance curve is 533kW. The power and torque curves of the engine and the brake specific fuel consumption with respect to engine speed are shown in Figure 2.

The generator output is computed based on the engine outputs and the approximated generator efficiency, η_{gen}. The relationship between the engine power and the generator power can be expressed as follows:

$$P_{gen} = P_{eng} * \eta_{gen} \tag{1}$$

where, P_{gen} is the generator power, P_{eng} is the engine power, and η_{gen} is the generator efficiency.

The fuel consumption of the engine can be calculated via the brake specific fuel consumption (BSFC) and the engine power as follows:

$$M_{eng} = 0.84 * 10^{-3} * BSFC * P_{eng} \tag{2}$$

where, M_{eng} is the engine fuel consumption (L/h), BSFC is the brake specific fuel consumption (g/kWh).

B. Battery and other power electronics models

The battery model is demonstrated by a simple equivalent circuit model in Figure 3. The battery power can be defined as follows:

$$P_{bat} = V_{oc} I_{bat} - I_{bat}^2 R_{bat} \tag{3}$$

where, V_{oc} is the open circuit voltage (OCV, V) of the battery, I_{bat} is the battery current (A), R_{bat} is the battery internal resistant (Ω). In this study, the battery power loss factor, $I_{bat}^2 R_{bat}$, is approximated by an efficiency term, η_{bat}.

The variation in battery state of charge (SOC) can be described by a state equation:

$$\dot{SOC} = -\frac{I_{bat}}{Q_{\max}} \tag{4}$$

where, Q_{max} is the battery capacity (Ah).

Thus, the SOC can be updated for step $(k+1)^{th}$ as follows:

$$SOC(k+1) = SOC(k) - \left[\frac{P_{bat}(k)\Delta T}{V_{oc}(k) Q_{\max} 3600}\right] \tag{5}$$

where, ΔT is the sampling period; $0\% \le SOC \le 100\%$.

The remaining power electronics on the DC grid is approximated by the general efficiency factor, η_{pe}.

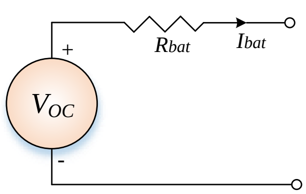

Figure 3. Battery equivalent circuit model

IV. Energy Management Strategy

Dynamic positioning vessels (DPVs) are an increasingly important part of the marine sector [7]. Computer controlled thrusters and other devices are used to maintain the positioning and heading of the vessel.

Considering the operating profile, the platform support dynamic positioning vessels may stay on station for several weeks at a time. Since an initial cruise from port begins, there is an extended period at much lower power. For reliability reasons, there needs to be sufficient power available to operate the control devices when needed in DP mode, so the generators are often running at low power and hence lower efficiency. A general operating profile of a DPV mainly consist of seven different modes: transit (cruising), DP loading (power demand is less), DP standby, harbour loading, harbour, emergency, and black start. Here, the first five modes are mostly operated and in the sequence of power request, from high to low.

For a voyage, after loading in harbour, the vessel transits to the area of operation. Most of the time (up to 80%) is then spent in DP loading mode, with periodic DP standby steps between operations. Finally, the vessel returns to port and unloads. Due to this complex profile with different power demand regions, the role of designing the EMS for a hybrid electric DPV is very important.

To simplify the system model and control design, some assumptions have been made as follows:

- The energy losses through power electronic devices can be assumed to be constants and represented by an efficiency coefficient.

- The energy losses through generators can be assumed to be constants and represented by an efficiency coefficient.

- The loads on motors and auxiliary loads can be represented as a dynamic load.

- The temperature impacts on the battery performance are not considered in this study.

The control diagram of the EMS for the DC HEMV is shown in Figure 4.

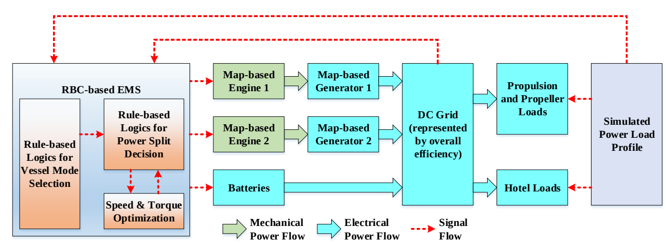

Figure 4. DC HEMV control diagram

The EMS is constructed based on the rule-based controller (RBC) with two rule sets. The first set of rules is used to design the working mode of the vessel based on the load demand. Next, the resulting mode and the current battery state are fed into the second rule set to define the power distribution between the generators and battery. The power requested on the generators is then sent through a simple optimization procedure to identify the optimal torque-speed demand for the diesel engine-generator. The final decision on power split between generators and battery is derived based on the desired torque-speed demands on the generators. It can be seen that the diesel generator can be operated at various speeds and torques in order to ensure that the engine can be operated at around the steady OOL. Therefore, the design of the RBC is to control the battery in such a way to allow either one or two engines to be turned off to save fuel consumption and emissions, and control the engine to operate at a point very close to the OOL, according to the current speed by regulating the battery flow. Based on the control diagram in Figure 4, the following rules are developed and apply to the controller.

- The *Pr* stands for power request, is the total propulsion load.

- PL, PM, PH are the low, medium, high levels of *Pr*. These levels are used to determine the working modes of the machine.

- If *Pr* is less than PL: the machine is decided to work in harbour (low power) mode;

- If *Pr* is equal or greater than PL but less than PM: the machine is decided to work in harbour – harbour loading mode;

- If *Pr* is equal or greater than PM but less than PH: the machine is decided to work in DP standby – DP loading mode;

- If *Pr* is equal or greater than PH: the machine is decided to work in cruising mode.

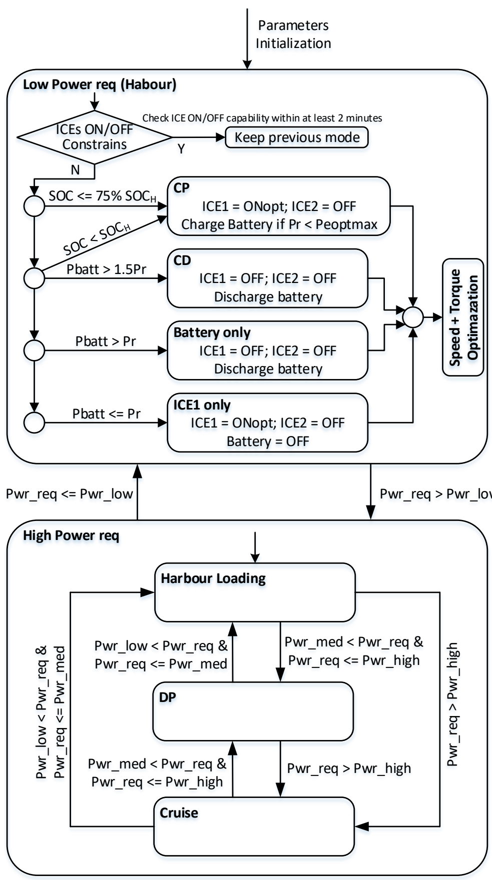

Figure 5a. EMS RBC strategy stateflow chart

Based on these designed rules, the EMS is built in MATLAB/Simulink environment using Stateflow toolbox. Figure 5a illustrates the EMS design diagram using Stateflow format while figure 5b demonstrates the detailed logic to define the power split between the generators and battery in harbour loading, DP and cruising modes, respectively.

Based on the power distribution output from the rule sets, the optimization procedure is employed to find the best instantaneous working point (torque and speed) for the generators closes to their OOL while satisfying the desired power request. If there is more than one optimal output power of the diesel-generator which meets the OOL, the one with smaller fuel consumption will be selected. Figure 6 shows the optimization strategy diagram of the engine speed and torque.

Finally, the power split ratio is derived based on the battery state of charge (SOC) level. Depending on the working modes and battery SOC levels, the battery can be selected to operate in various working modes such as: maximum discharge mode, optimal discharge mode, charge depleting mode, charge sustaining mode or charge priority mode. To avoid continuous switching between working modes, small values are added to the thresholds.

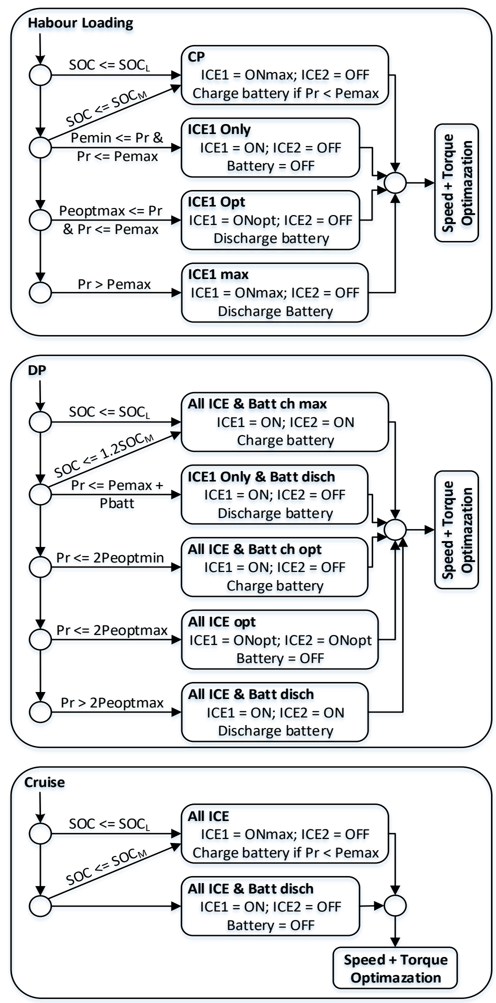

Figure 5b. Power split in harbour loading, DP and cruising modes

During operation, the diesel-generator can be turned off if the energy in the battery is sufficient to supply the whole system over the desired minimum period (calculated based on the current working mode); and the period of time between two continuous engine cranking events is selected properly (decided based on engine-generator dynamics). In this study, the desired minimum period of time for the system running under the battery only and the minimum period of time between two continuous engine cranking events are both set to 2 minutes.

V. Numerical Simulation Results

A. Simulation setup

The simulation model is built in Matlab/Simulink environment and is shown in Figure 7. The operating load profile, vessel's mathematical model, EMS based on RBC strategy and working temperature are included in the proposed model, the battery capacity is selected as 480V 500Ah, the maximum peak discharge current of the battery is 1000Ah.

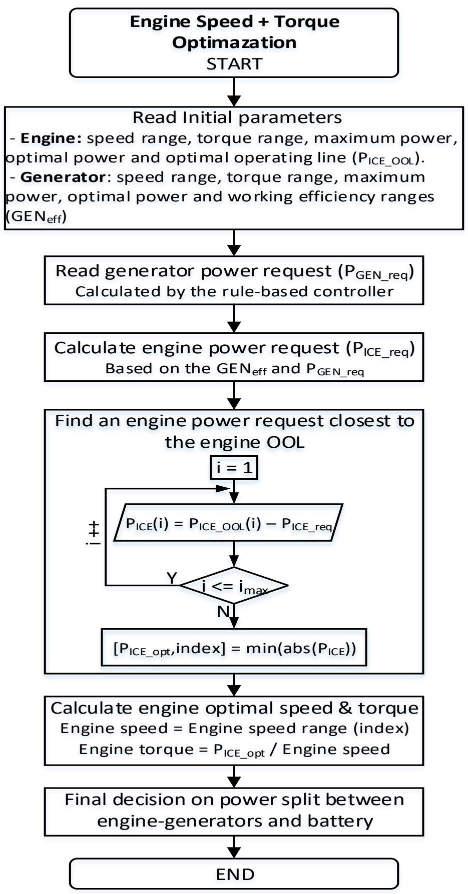

Figure 6. Engine speed and torque optimization

The simulation is performed based on a 5-operation-modes load profile which combines both propulsion load and hotel load of the vessel during 17.5 hours of operating. The sampling time is set to 1 second. The employed load profile with different operating modes is demonstrated in Figure 8.

The initial battery SOC is set to 85%. To prevent over-charging and over-discharging, the upper and lower thresholds for charging and discharging are set to 90% and 10%, respectively.

B. Simulation results and discussions

The simulations are performed to evaluate the performance of the proposed HEMV model. The power distribution between the diesel-generators and the battery is shown in Figure 9. It can be seen that, during the operation, the diesel-generators can be shut down at some points where the energy in the battery is sufficient and enough to supply the system over a period of time, otherwise, the engines will be turned on to drive the system. Depending on the current operation mode, the battery can be charged or discharged to maximize the performance of the system.

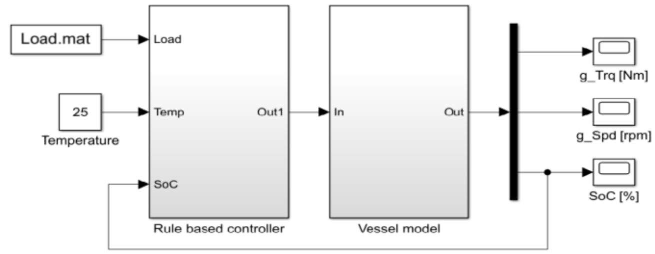

Figure 7. DC HEMV Simulation model.

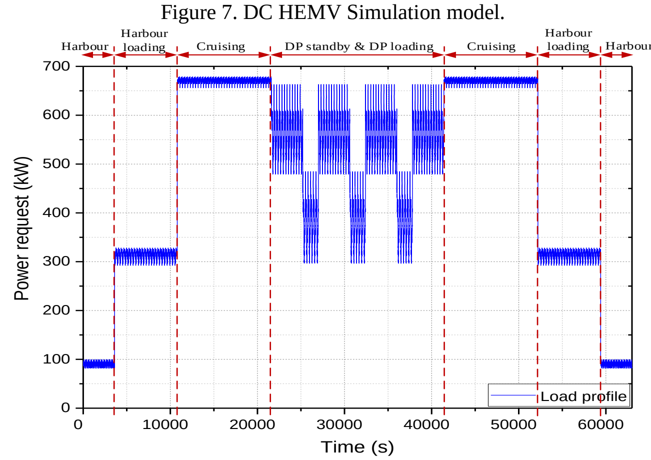

Figure 8. Five-operation-modes load profile

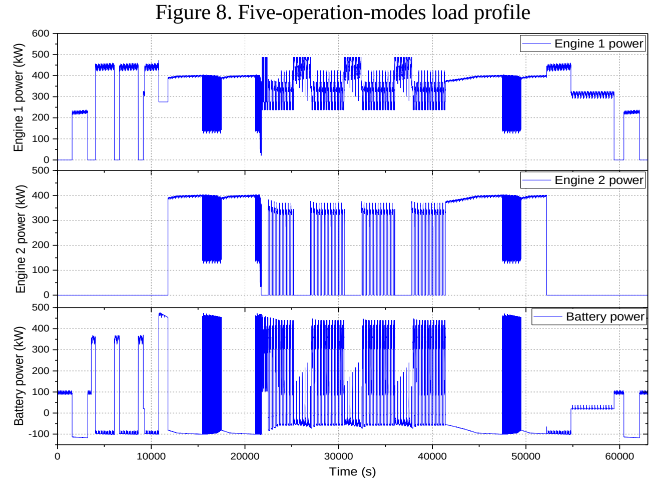

Figure 9. Power distribution of diesel-generators and battery.

The advantage of the proposed RBC strategy is that it tries to drive the diesel engines to operate at some points very close to the static OOL of the engines, where the performance of the engine is at a maximum and has a low power consumption. The speed and torque request of diesel-generator 1 are given in Figure 10. The engine speed and torque are adjusted in such a way that the engine can work closely to its OOL and, therefore, the fuel consumption can be minimized. Figure 11 show the simulation results of the engine working points compared to the OOL. The engine power matches well with the OOL.

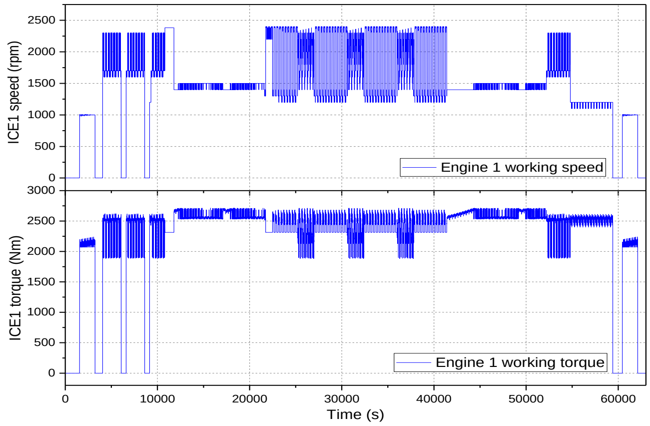

Figure 10. Speed and torque request of diesel-generator 1.

The remaining power request or the remaining power of the engine-generators after delivering to the system are compensated by the battery power which is representing as the discharging and charging energies of the battery. Figure 12 shows the start/stop sequences of the diesel engine-generators and the SOC performance of the battery during the operation of the system.

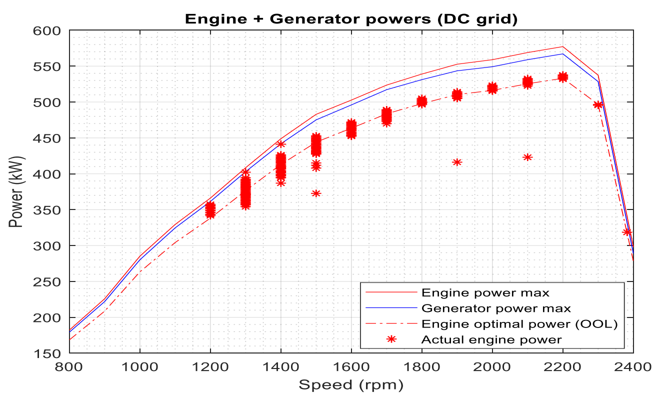

Figure 11. Engine working power in the OOL

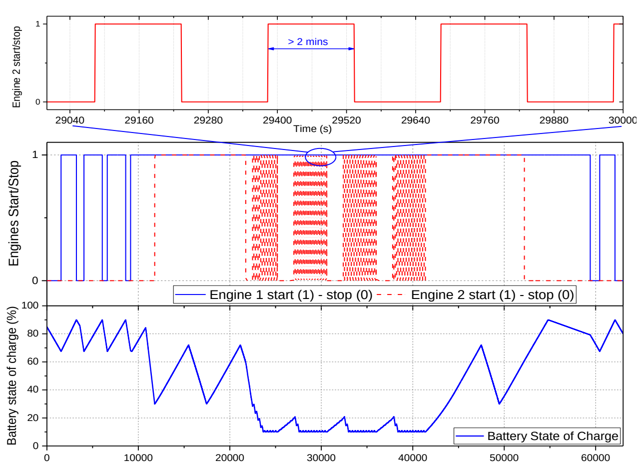

Figure 12. Engines start/stop sequences and battery SOC.

The brake specific fuel consumption (BSFC) of diesel engine 1 and the total fuel consumption of the engines are displayed in Figure 13. The engine total fuel consumption can be reduced by controlling the start/stop sequences of the engines and optimizing the speed and torque of the engines so that they can work at the nearest points of the OOL, the fuel consumption is therefore improved significantly.

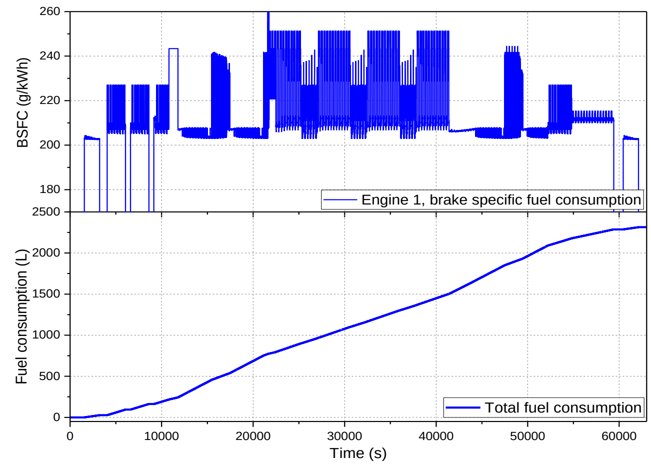

Fig. 13. BSFC and total fuel consumption of the engines.

VI. Conclusions

This study investigated the implementation of a hybrid electric propulsion system for marine vessels. The engines were simply represented based on the steady OOL of the Caterpillar engine to evaluate the controller. The control strategy based on the RBC was successfully employed to drive the system in such a way to maximize the engines performance and to achieve the benefits in term of fuel consumption and gas emissions. Furthermore, the use of hybrid electric propulsion could lead to a reduction of working noise on board marine vessels due to optimizing the start-stop process of the diesel engines.

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