Optimal Control and Real-Time Simulation of Hybrid Marine Power Plants

Truong Quang Dinh[a,*], Truong Minh Ngoc Bui[a], James Marco[a], Chris Watts[b]

[a]*Warwick Manufacturing Group (WMG), University of Warwick, Coventry, CV4 7AL, UK*
[b]*Babcock International Group, Leicester, LE3 1UF, UK*
* Corresponding Author. Email: q.dinh@warwick.ac.uk

Synopsis

With significantly increasing concerns about greenhouse effects and sustainable economy, the marine industry presents great potential for reducing its environmental impact. Recent developments in power electronics and hybridisation technologies create new opportunities for innovative marine power plants which utilize both traditional diesel generators and energy storage like batteries and/or supercapacitors as the power sources. However, power management of such complex systems in order to achieve the best efficiency becomes one of the major challenges.

Acknowledging this importance, this research aims to develop an optimal control strategy (OCS) for hybrid marine power plants. First, architecture of the researched marine power plant is briefly discussed and a simple plant model is presented. The generator can be used to charge the batteries when the ship works with low power demands. Conversely, this battery energy can be used as an additional power source to drive the propulsion or assist the generators when necessary. In addition, energy losses through braking can be recuperated and stored in the battery for later use. Second, the OCS is developed based on equivalent fuel consumption minimisation (EFCM) approach to manage efficiently the power flow between the power sources. This helps the generators to work at the optimal operating conditions, conserving fuel and lowering emissions. In principle, the EFCM is based on the simple concept that discharging the battery at present is equivalent to a fuel burn in the future and vice-versa and, is suitable for real-time implementation. However, instantaneously regulating the power sources' demands could affect the system stability as well as the lifetime of the components. To overcome this drawback and to achieve smooth energy management, the OCS is designed with a number of penalty factors by considering carefully the system states, such as generators' fuel consumption and dynamics (stop/start and cranking behaviour), battery state of charge and power demands. Moreover, adaptive energy conversion factors are designed using artificial intelligence and integrated in the OCS design to improve the management performance. The system therefore is capable of operating in the highest fuel economy zone and without sacrificing the overall performance. Furthermore, a real-time simulation platform has been developed for the future investigation of the control logic. The effectiveness of the proposed OCS is then verified through numerical simulations with a number of test cases.

Keywords: Marine vessel; Hybrid propulsion; Energy management; Diesel generator, Battery, Optimisation

1. Introduction

The global energy crisis and environmental pollution have led to significant demands for a revolution of low-carbon and energy-saving technologies across industries (HM Government, 2011). Meanwhile, the shipping industry is recognised as one of the industries having major impact on global fuel consumption and emissions (Third IMO greenhouse gas study 2014, 2015). High demand for maritime transport leads to a wide variety of operational profiles and therefore, a large volume of fuel consumption in ships, especially large vessels. To tackle these challenges, hybrid electric propulsion combining a traditional diesel generator-powered propulsion with an energy storage system utilising, for example, batteries or super capacitors is considered as a feasible solution (Dedes et al., 2012; Doerry et al., 2015; Skjong et al., 2016). However, managing a hybrid powertrain with a number of engine-generators and batteries to achieve low levels of energy consumption and emissions while maximising the machine performance is one of the critical issues hindering its application in the shipping industry. In addition, continuous fluctuations of loads on the vessel propulsion could affect the system stability as well as the lifetime of the components.

Development of agile energy management strategies (EMSs) for hybrid marine ships is considered as the key to success and, therefore, draws great attention from both academia and industry. To achieve this goal, a number of EMSs for different ship classes of hybrid electric ships have been introduced (Wang et al., 2008; Zahedi et al., 2014). Hou et al. (2014) introduced a power management system utilising model predictive control to mitigate power fluctuations in an electrical ship propulsion. To efficiently manage the power flows between engines and batteries of a hybrid electric tugboat, Vu et al. (2015) explored benefits of employing both optimisation and prediction techniques to design the EMS. Consequently, the improved operational performance with fuel savings could be achieved by using these methods. However, their real-time applications are limited due to the complexity of the control logic and their dependencies on the system and environment knowledge as well as the prediction performance. Recently, equivalent fuel consumption minimisation technique has been introduced as a powerful online optimisation tool and primarily utilised for EMS of hybrid electric vehicles (Nüesch et al., 2014). EFCM is based on the simple concept that any battery energy discharged at present is equivalent to a fuel burn in the future to charge this energy back to the battery, and vice-versa. By using this concept, the sum of actual fuel consumed by the engines and actual energy flow through the battery at the given moment can be represented by the so-called total equivalent fuel consumption and, subsequently, the fuel consumption minimisation can be easily addressed. Due to this unique feature, EFCM has started to be used in other sectors, including marine applications. Yuan et al. (2016) employed EFCM to hybrid electric tugboats to perform the online power split optimisation. This technique could drive the generators to their optimal operating conditions, conserving fuel and lowering emissions. Nevertheless, the conversion from electric energy to fuel energy was fixed during the optimisation and the engine-generator switching frequency was not discussed.

This research focuses on the development of an OCS for energy management of hybrid marine power plants. For this purpose, a dynamic positioning hybrid marine vessel (BØ et al., 2016) has been chosen as the targeted system. First, the system description and its simple mathematical model is briefly discussed. Next, the OCS is developed based on an EFCM algorithm to manage efficiently the power flow between the power sources. To overcome the drawback in the traditional EFCM and to achieve the smooth energy management, the OCS is designed with a number of penalty factors by considering carefully the system states, such as generators' fuel consumption and dynamics (stop/start and cranking behaviour), battery state of charge and power demands. Moreover, adaptive energy conversion factors are designed using fuzzy logic and integrated in the OCS design to improve the control performance. The system therefore is capable of operating in the highest fuel economy zone and without scarifying the overall performance. A real-time simulation platform has been developed for the future investigation of the control logic. Finally, the effectiveness of the proposed OCS is then verified through a comparative study between this OCS and other control schemes via numerical simulations.

2. Hybrid vessel propulsion

2.1. System description

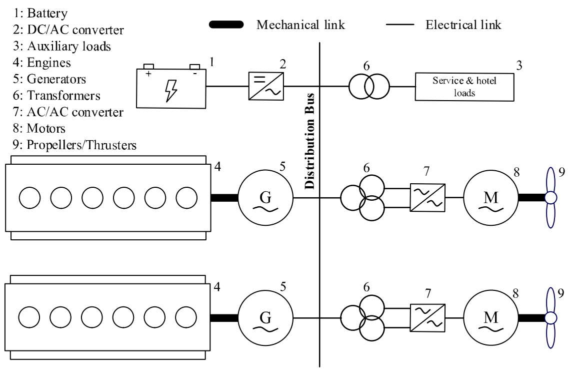


Figure 1: Generic propulsion architecture of a hybrid electric vessel

Propulsion architecture of a typical hybrid electric vessel is depicted in Figure 1. Generally, the system includes: (1) Power sources, engine-generators and battery, to generate electricity for an AC distribution bus; (2) Transformers and power converters to distribute electricity to propellers, thrusters and auxiliary (hotel).

A dynamic positioning ship employs an automatic control system capable of maintaining its position and heading by using its own thrusters and propellers. Because of this advanced feature, this type of vessels accounts for a crucial portion of the marine sector (such as cruise ships, cable-laying ships, flotels, and supply vessels) (DP & Marine Assurance Norway AS, 2018).

Operation of a DP vessel normally follows seven modes: harbour, harbour loading, transit (cruising), DP loading, DP standby, emergency, and black start. For each voyage, the vessel transits to an area desired for operations after loading in harbour at port. It may stay stationary there for a few hours to a few weeks to perform given tasks. The vessel then spends most of its time, and thus energy, in DP loading and DP standby modes (high power demands) before returning to port to unload. In order to ensure the vessel performance in these modes as well as its ability to adapt quickly to any peak loads, the traditional propulsion system needs to have a power capacity much higher than the average power required to operate the vessel. As a result, this leads to the selection of large size engine-generators but running in low power and, therefore, low efficiency regions.

To address the design and control challenges of DP vessels, a hybrid propulsion system using batteries is known as a feasible solution due to its potential benefits. First, the utilisation of batteries allows an optimal control of energy flow between engine-generators and batteries. Depending on load demands and battery energy, one or more engines to be turned off and on to avoid operating in low efficiency zones. This results in significant improvements in fuel consumption, emissions and noise-vibration-hardness level of the engines. Second, similar to automotive applications (Son et al., 2018) the use of batteries offers the load levelling function in energy management. By using this function, engine-generators can work at their optimal constant working points with the highest energy efficiency disregarding the actual load fluctuations by dis-charging or re-charging batteries. Third, batteries can provide other advanced features, such as peak shaving (to avoid the need of large power sources to supply peak demands of highly variable pulsed loads, i.e. naval weapons and high-power radar) (Dedes et al., 2012), brake energy recuperation and back-up power (Geertsma et al., 2017). In order to enhance these functions, an agile control scheme is necessary to decide working profiles of engine-generators and batteries in such a way that the fuel consumption and emissions of the engines are minimised while the machine performance is guaranteed (Sun, 2015).

2.2. Simple hybrid vessel model

In order to develop the proposed EMS, a backward facing model of the hybrid vessel is constructed based on the following assumptions:

- Transient responses of power electronics and engine-generators are not considered in this study. Energy losses through the power grid are assumed constant and represented by a fixed efficiency value. Meanwhile, energy losses through the engines and generators are represented by an engine break specific fuel consumption (*BSFC*) map and a generator efficiency map, respectively.
- During simulations, impacts of temperature on the system performance are not considered.
- Total propulsion and hotel loads are represented by a dynamic load profile.

2.2.1. Diesel engine and generator models

The generator can be characterised by its efficiency map (η_{gen}). For the AC grid, the AC frequency (denoted as f_{gen}) needs to be maintained at a desired value depending on the type of generator and working condition. The frequency and the generator torque (denoted as τ_{gen}) can be derived as:

$$f_{gen} = \frac{Pl_{gen} n_{gen}}{120} \tag{1}$$

$$\tau_{gen} = \frac{P_{gen}}{n_{gen} \eta_{gen}} \tag{2}$$

where P_{gen}, n_{gen}, Pl_{gen} and η_{gen} are in turn the output power, working speed, number of poles and efficiency of the generator.

The engine is represented by a performance map as plotted in Figure 2 which shows the relation of engine torque, power and *BSFC* to speed. Here, the map is generated from a 553kW Caterpillar engine. The instantaneous engine consumption rate (l/hr), $\dot{M}_{eng}$, can be computed as:

$$\dot{M}_{eng} = 0.84^{-1} BSFC \frac{P_{eng}}{1000} \tag{3}$$

where P_{eng} is the engine output power; and the diesel density is 0.84kg/l.

The relationship between the output powers of engine and generator can be expressed as:

$$P_{gen} = P_{eng} \eta_{gen} \tag{4}$$

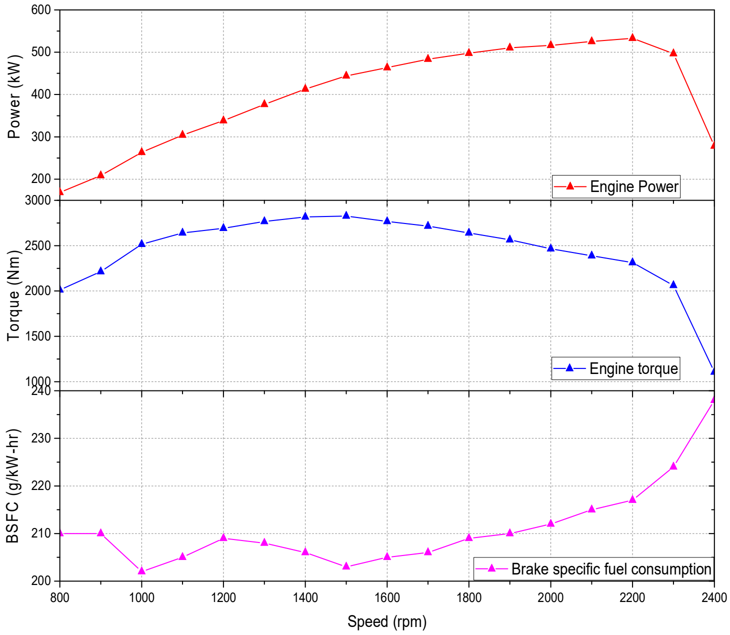


Figure 2: Engine performance map

2.2.2. Battery and power electronic models

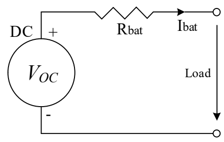


Figure 3: Battery equivalent circuit model

The battery is represented by a simple equivalent circuit model as depicted in Figure 3. The battery power can be then computed as:

$$P_{bat} = V_{oc} I_{bat} - I_{bat}^{\ 2} R_{bat} \tag{5}$$

where: V_{oc} is the open circuit voltage (*OCV*); I_{bat} is the battery current; R_{bat} is the internal resistance.

The battery state of charge (*SOC*) can be defined as:

$$\dot{SOC} = -\frac{I_{bat}}{Q_{\max}} \tag{6}$$

where Q_{max} is the maximum battery capacity.

From (6), the *SOC* can be updated for step $(k+1)^{th}$ as follows:

$$SOC\,(k+1) = SOC\,(k) - \left[\frac{P_{bat}\,(k)\Delta T}{V_{oc}\,(k) Q_{\max}\,3600}\right] \tag{7}$$

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

Finally, the power electronics of the propulsion system are approximated by a fixed efficiency factor, η_{pe} .

3. Optimal control strategy

3.1. *Energy management overview*

The OCS-based energy management configuration for a hybrid vessel is depicted in Figure 4. Here, the propulsion system is assumed to be driven by three power sources, two engine-generators and one battery. The EMS receives the load demands on the AC grid in order to drive these power sources using the optimal control strategy via the 'Power Split Decision' block. The OCS is designed in such a way that: the engine-generators run at their desired speeds to stabilize the AC grid frequency; the battery enhances the load levelling concept which allows the engines not only to operate as close as possible to their optimal operating points but also to be shut down and therefore, enables fuel savings and emission reductions. Thus, the EMS is proposed as the combination of three main control units: a simple rule-based classifier (RBC) to classify the system working modes according to the load demand levels; an EFCM algorithm to define instantaneously the optimal power split ratio between the engine-generators and the battery; and a gain tuner to regulate adaptive energy conversion gains of the EFCM according to the battery performance. The details of these control blocks are described through the following sections.

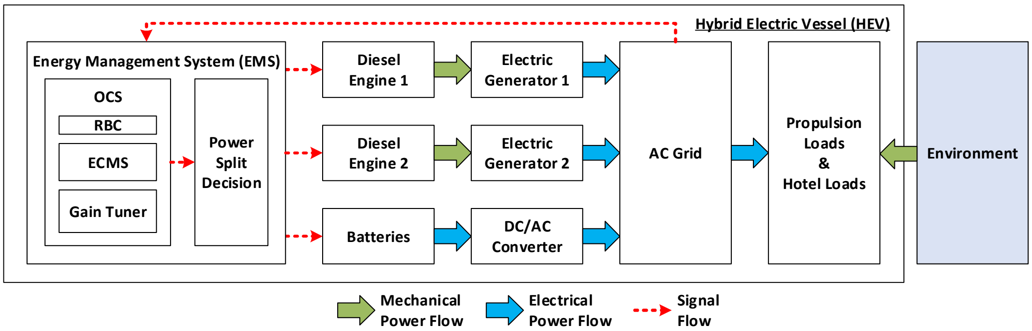


Figure 4: Energy control diagram for hybrid vessel

3.2. *EFCM design*

In this section, the EFCM design for application to the hybrid vessel is introduced. From Figure 4, according to the load demands, the total power request (P_{req}, kW) for the power sources (engine and battery) can be expressed as:

$$P_{req} = (P_{eng,1} + P_{eng,2}) + P_{bat} \tag{8}$$

Define u as the power split ratio:

$$u = \frac{P_{bat}}{P_{req}} \tag{9}$$

Thus, power commands for the engines can be calculated as:

$$\begin{cases} P_{eng,1} = P_{req}\left(1-u\right) & \text{IF: gen. 2 is OFF} \\ P_{eng,1} = P_{eng,2} = \dfrac{P_{req}\left(1-u\right)}{2} & \text{IF: 2 gen. are ON} \end{cases} \tag{10}$$

Proper constraints for the component power requests and the battery SOC are set based on the system specifications:

$$\begin{cases} 0 \le P_{eng,1}, P_{eng,2} \le P_{eng}^{\max} \\ P_{bat}^{\text{charge\_max}} \le P_{bat} \le 0 \text{ or } 0 \le P_{bat} \le P_{bat}^{\text{discharge\_max}} \\ SOC_{\min} \le SOC \le SOC_{\max}; -1 \le u \le 1 \end{cases} \tag{11}$$

here: $P_{eng}^{\max}$ is the maximum power provided by each engine; $P_{bat}^{\text{charge\_max}}$ and $P_{bat}^{\text{discharge\_max}}$ are in turn the maximum charge and discharge powers of the battery; SOC_{min} and SOC_{max} are in turn the minimum and maximum values of *SOC* defining the most suitable operating range of the battery.

As shown in (9), the engine-generators can be turned off and on during the operation by using the battery. However, due to the large inertia of engine-generators, especially in the cranking phase, as well as the component lifetime, two constraints are added to the EFCM design as follows:

- Constraint 1 - minimum engine-off period, which is defined as the time needed to crank the engine from zero rpm to its desired speed.
- Constraint 2 – minimum engine-on period, which can be properly selected by considering impacts, such as number of ON/OFF and thermal loads, on the component lifetime (such as engine-generators and power electronics).

By adding these constraints, the engine is only turned off if: (1) the energy provided by the battery and the remaining generators (if necessary) is still sufficient to supply an average energy (calculated based on the current working mode) over the minimum engine-off period; and (2) the engine already operates longer than the minimum engine-on period.

The EFCM is then designed based on the concept of equivalent energy consumption. For a propulsion system consisting of engines and a battery like this hybrid vessel, a discharge from batteries at present will lead to a future equivalent charge to the battery by the engines burning fuel. On the contrary, a charge to batteries at present will allow a future equivalent discharge from the battery to assist engines, saving fuel. Thus, the EFCM algorithm is developed based on a pre-defined cost function *J* which is the total equivalent mass-burning rate per unit time (second) of the targeted system:

$$J = \sum_{i=1}^{2} \dot{m}_{eng,i}^{fuel} + \dot{m}_{bat}^{fuel} \tag{12}$$

where $\dot{m}_{eng,i}^{fuel}$ is the mass-burning rate per unit time of engine i^{th} which can be computed using (13) ; $\dot{m}_{bat,j}^{fuel}$ is the total equivalent mass-burning rate per unit time of *m* batteries derived from (14).

$$\dot{m}_{eng,i}^{fuel} = C_{eng,i} P_{eng,i} \tag{13}$$

$$\dot{m}_{bat}^{fuel} = C_{bat} P_{bat} \tag{14}$$

where $C_{eng,i}$ and C_{bat} are the conversion factors; $C_{eng,i} = BSFC(P_{eng,i})$; meanwhile C_{bat} is designed as:

$$C_{bat} = \begin{bmatrix} \alpha_C \left(1 - \beta_C \left(SOC - SOC_{\text{med}}\right)\right), IF \text{ BAT is Charged} \\ \alpha_D \left(1 - \beta_D \left(SOC - SOC_{\text{med}}\right)\right), IF \text{ BAT is Discharged} \end{bmatrix} \tag{15}$$

where $\{\alpha_C, \beta_C\}$ and $\{\alpha_D, \beta_D\}$ are the adaptive energy conversion gains of the battery equivalent consumption during charge and discharge, respectively; $SOC_{\text{med}} = 0.5\left(SOC_{\min} + SOC_{\max}\right)$.

From (8) to (15), the optimal control problem using EFCM is to minimise the cost function *J* subject to a set of different power split ratios and the set of system constraints:

$$\min_{\substack{\{u_k\} \\ Constrains}} J = \min_{\substack{\{u_k\} \\ Constrains}} \left(\sum_{i=1}^{2} C_{eng,i}\left(u_k\right) P_{eng,i}\left(u_k\right) + C_{bat}\left(u_k\right) P_{bat}\left(u_k\right) \right) \tag{16}$$

3.3. Gain tuner design

As described in the previous sections, the adaptive energy conversion gains in (15) are regulated online using the gain tuner to improve the EFCM performance. Here, a fuzzy controller with two inputs and four outputs is introduced to construct the gain tuner. The two fuzzy inputs are the battery *SOC* and its derivative (*dSOC*/*dt*). Meanwhile the four fuzzy outputs are named as $d\alpha_C, d\beta_C, d\alpha_D$ and $d\beta_D$ which are utilised as follows:

$$\begin{cases} \alpha_C(k+1) = \alpha_C^0 + k_1 d\alpha_C(k) \\ \beta_C(k+1) = \beta_C^0 + k_2 d\beta_C(k) \\ \alpha_D(k+1) = \alpha_D^0 + k_3 d\alpha_D(k) \\ \beta_D(k+1) = \beta_D^0 + k_4 d\beta_D(k) \end{cases} \tag{17}$$

where $\alpha_C^0, \beta_C^0, \alpha_D^0$ and β_D^0 are the initial values of the adaptive gains; k_1, k_2, k_3 and k_4 are the scaling gains.

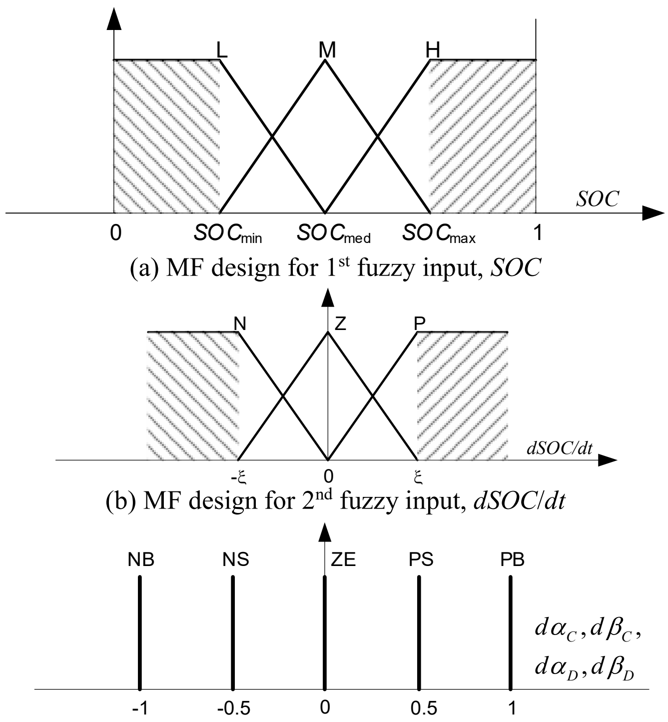
For the fuzzy design, triangle membership functions (MFs) are used to represent the inputs while singleton MFs are used to represent the outputs. The first fuzzy input, *SOC*, is described by three MFs named L ($SOC_{\min}$), M (SOC_{med}), and H ($SOC_{\max}$) as shown in Figure 5(a). The second fuzzy input, *dSOC*/*dt*, is described by three MFs named N (Negative change), Z (Zero change), and P (Positive change) as shown in Figure 5(b) (please note that ξ is the small value of *SOC* change defined based on the battery specifications and sampling rate).

Each MF of each input variable can be expressed as follows:

$$f_j(x_i) = \begin{cases} 1 + \left(x_i - a_{ij}\right)/b_{ji}^- & \text{if } \left(-b_{ij}^-\right) \le \left(x_i - a_{ij}\right) \le 0 \\ 1 - \left(x_i - a_{ij}\right)/b_{ij}^+ & \text{if } 0 \le \left(x_i - a_{ij}\right) \le \left(b_{ij}^+\right) \\ 0, \text{otherwise}; & i \in [1,2];\ j \in [1,2,3] \end{cases} \tag{18}$$

where $(x_1 \equiv SOC; x_2 \equiv dSOC/dt)$; a_{ij}, b_{ij}^- and b_{ij}^+ are the centroid, left half-width, right half-width of MF j^{th} of input i^{th}, respectively.

The four fuzzy outputs are described by five MFs named NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), and PB (Positive Big) as shown in Figure 5(c).



(a) MF design for 1st fuzzy input, *SOC*

(b) MF design for 2nd fuzzy input, *dSOC*/*dt*

(c) MF design for fuzzy outputs, $d\alpha_C, d\beta_C, d\alpha_D$ and $d\beta_D$

Figure 5: Input/output design of the fuzzy tuner

Next, the well-known max-min and centroid approaches are employed for the fuzzy inference and defuzzification (Truong and Ahn, 2011). Hence, each fuzzy output can be derived using the defuzzification as follows:

$$d_{fuzzy} = \sum_{m=1}^{5} mf\left(w_m\right) w_m \bigg/ \sum_{m=1}^{5} mf\left(w_m\right), \left(d_{fuzzy} \text{ is } d\alpha_C, d\beta_C, d\alpha_D, \text{or } d\beta_D\right) \tag{19}$$

where w_m is the weight of MF m^{th} of the d_{fuzzy} output; $mf(w_m)$ is the fuzzy output function given by

$$mf\left(w_m\right) = \sum_{j,k} mf_{jk}\left(w_m\right) \tag{20}$$

where $mf_{jk}(w_m)$ is the consequent fuzzy output function when the first and second inputs are in classes j^{th} and k^{th}:

$$mf_{jk}\left(w_m\right) = \delta_{jk}\mu_{jk} \tag{21}$$

where δ_{jk} is the activation factor, which is activated when input x_1 is in class j^{th}, and input x_2 is in class k^{th}; μ_{jk} is the height of the consequent fuzzy function obtained from the inputs:

$$\mu_{jk} = \min\left[f_j\left(x_1\right), f_k\left(x_2\right)\right] \tag{22}$$

Finally, to support the fuzzy defuzzification (19), a rule table is established in Table 1 based on the sets of MFs designed for the fuzzy inputs/outputs. Three MFs for each input lead to the total 9 rules for each output by using an IF-THEN structure as follows:

RULE i^{th}: IF SOC is A_i and $dSOC/dt$ is B_i THEN fuzzy output k^{th} is C_i ($i = 1,...;9$; $k = 1,...,4$) (23)

where A_i, B_i, and C_i are MF i^{th} of the input and output variables used in the fuzzy rules.

Table 1: Rule table for the fuzzy defuzzification

$\{d\alpha_C, d\beta_C, d\alpha_D, d\beta_D\}$		*SOC*		
		L	M	H
dSOC/dt	N	{NB,NB,PB,PB}	{NB,ZE,PB,ZE}	{ZE,PS,ZE,NS}
	Z	{NB,NS,PB,PS}	{NS,ZE,PS,ZE}	{PS,ZE,NS,ZE}
	P	{NS,NB,PS,PB}	{ZE,NS,ZE,PS}	{PB,NS,NB,PS}

3.4. RBC design

To design the RBC, two thresholds are defined as the low and medium levels of P_{req}, respectively, in which $P_L \equiv P_{eng}^{opt} < P_{eng}^{\max}$ and $P_M \equiv P_{eng}^{\max}$ (P_{eng}^{opt} is the power when the engine runs at its optimal operating point providing the highest energy efficiency). Three rules are then designed using these thresholds and therefore, the proposed EMS algorithm to optimise the system power split ratio is calculated using the following procedure (combining the RBC and the EFCM):

- Rule 1: $P_{req} \le P_L$

  If battery SOC level is sufficient, turn off both engines and run system using only battery ($u = 1$);

  Else, turn off 2nd engine, assign $u = \{-1,...,1\}$ and replace into the optimisation problem (16) to find the optimal u (u_{opt}).

- Rule 2: $P_L < P_{req} \le P_M$

  + Turn off 2nd engine and run system using battery and 1st engine;

  + Assign $u = \{-1,...,1\}$ and replace into the optimisation problem (16) to find u_{opt}.

- Rule 3: $P_{req} > P_M$

  + Run system using both battery and engines;

  + Assign $u = \{-1,...,1\}$ and replace into the optimisation problem (16) to find u_{opt}.

4. Real-time simulation

Real-time simulation (RT-Sim) platforms have been widely used by both researchers and manufacturers for product development and rapid prototyping (Yi et al., 2016). To construct a RT-Sim platform, a physical system is represented by an equivalent model running on a hardware and interfacing with control systems and/or other equipment in real-time. A RT-Sim platform is capable of replicating the working conditions that the system will operate in the real world. This allows both the system model and control logic to be validated quickly and safely in real-time. Hence, doing experiments on a RT-Sim platform is the time efficient and cost effective way to bridge the gap between theoretical research and real-time implementation of new systems and control algorithms (Truong et al., 2017).

To evaluate the effectiveness as well as applicability of the proposed OCS in actual conditions, a simple but efficient RT-Sim platform for hybrid marine power plants has been developed during this research. The RT-Sim platform is built with two operation modes: Mode-1 – to investigate the effectiveness of the EMS in real-time environment; Mode-2 – to evaluate the applicability of the EMS, with the system using industrial communication protocols, such as CAN and Ethernet.

4.1. RT-Sim platform design

The RT-Sim platform has been built in the Control Laboratory at WMG – the University of Warwick using real-time machines from dSPACE as shown in Figure 6. The RT-Sim platform consists of three main dSPACE modules: a SCALEXIO to represent the propulsion system excluding the battery pack and the energy management system; a battery emulator (BAT-E) to represent the battery pack; and a MicroAutoBox (MAB) connecting with the BAT-E to function as the battery management system with basic functions to control and monitor the BAT-E. The tools from MATLAB and dSPACE including Real Time Interfaces (RTI) MultiMessage Blockset, RTI Ethernet Blockset, Simulink Coder (automatic code generation), ConfigurationDesk and ControlDesk are utilized for building the C-codes to run on the dSPACE machines. Here, for simulations with Mode-1, the whole propulsion model including battery model is built with the EMS in the real-time environment within the SCALEXIO only (the MAB and BAT-E are not activated in this mode). For simulation with Mode-2, the SCALEXIO communicates with the MAB using CAN channels while the MAB interacts with the BAT-E via Ethernet. To ensure the real-time operation as well as network traffic, the communication status between these two devices, SCALEXIO and MAB, are monitored using a CANalyzer. Finally, a PC installed ControlDesk is used to manage the simulation platform as well as to record test results.

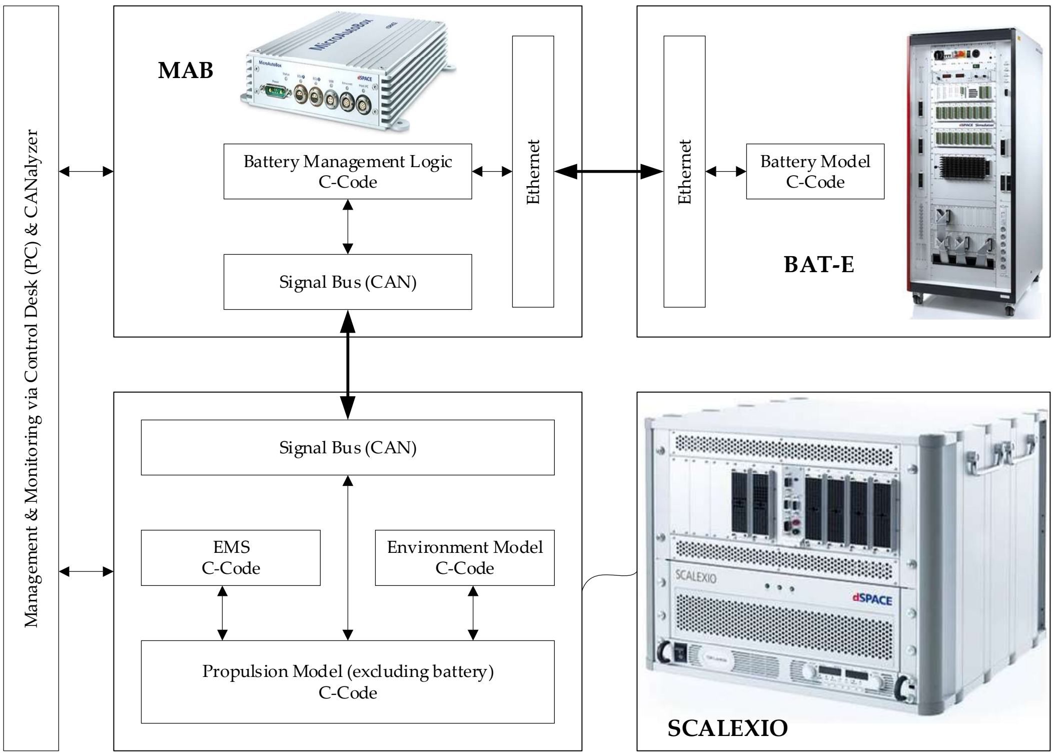


Figure 6: Configuration of the RT-Sim platform

4.2. *Test scenario setup*

To support the control system evaluation, the vessel model presented in Section 2.2 was constructed in MATLAB/Simulink. Here, a battery with voltage of 480V DC, current of 500Ah and peak discharge current of 1000Ah was selected to form the model. The battery model was allowed to work within a *SOC* range of [10, 90]% and the initial *SOC* value was set to 85%. For the simulations, a load profile representing the total propulsion and hotel loads over the five basic modes of a DP vessel for a complete voyage was created as plotted in Figure 7. The sampling period of the control system was set to 1 second.

To demonstrate the advantages of the OCS, a comparative study between this proposed approach and three other energy management approaches was performed. The first one was a load following controller for the traditional propulsion system without using battery. In this control concept, both the engine-generators were kept running at the desired constant speed to maintain the grid frequency setting while their torque commands were directly regulated by the load demands. The second scheme was the rule-based controller, RBC, introduced in Section 3.4. The power requested to the power sources and the ON/OFF commands for the engines were then derived based on the load demands and SOC level. The third control scheme was the EFCM designed in Section 3.2. In this case, the energy conversion gains in (15) were properly selected and fixed during the system operation.

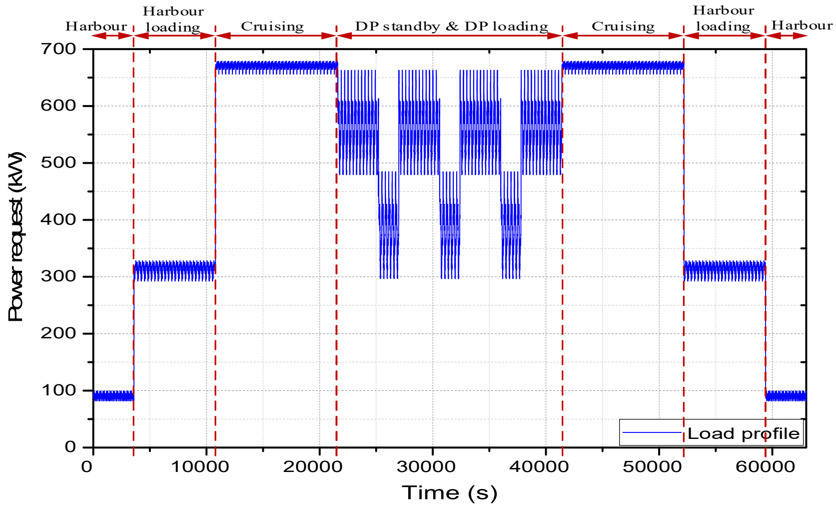


Figure 7: Designed load profile

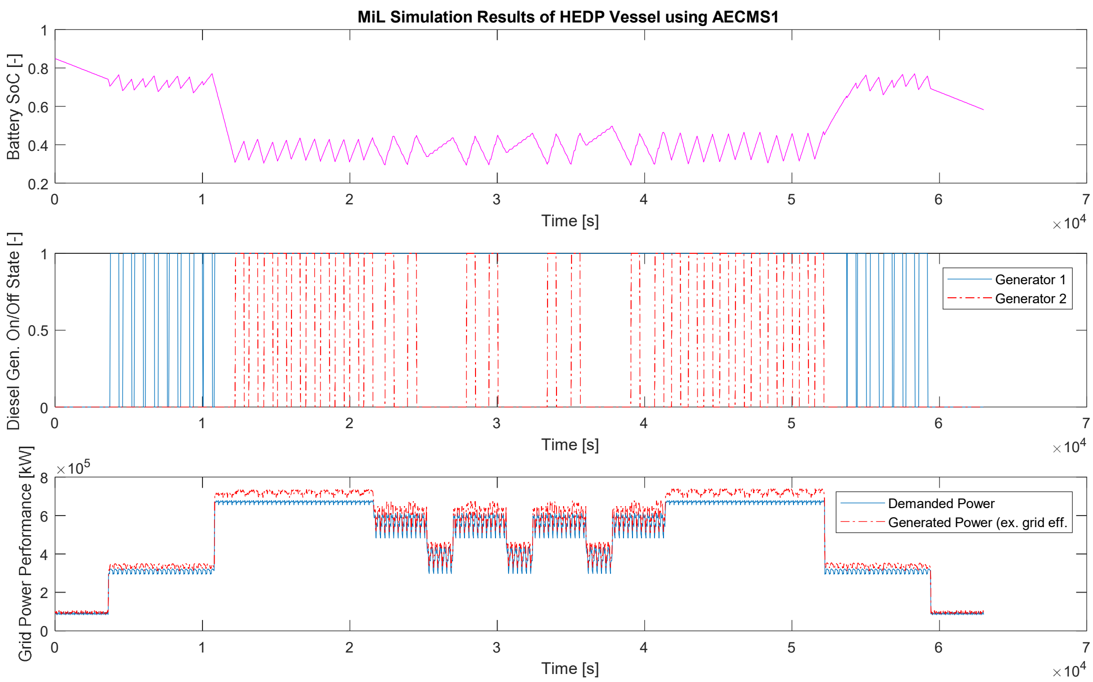


Figure 8: Power distribution between generators and battery

4.3. Simulation results

This study focuses on the effectiveness of the proposed energy management approach over traditional schemes. Thus, only Mode-1 of the RT-Sim platform was utilised. Real-time simulations with the vessel model using the three controllers under the given loads were then carried out.

First, the simulation results of the proposed OCS were obtained and plotted in Figure 8. The bottom sub-plot in this figure is the comparison between the demanded power (solid blue line) and the total power consumed by the AC network (dash-dot red line). It should be noted the gaps between the demanded power and the consumed power were the total power lost through the powertrain due to the component efficiencies, including power electronics efficiency, generator efficiency and battery charge/discharge efficiency. The largest gap was therefore recognised while both the generators and battery were used. The middle and top sub-plots of Figure 8 show the ON/OFF states of the engine-generators and the battery SOC profile, respectively. The result indicates that the battery was used in case the system ran at low loads. One or both the engine-generators was turned off to save energy in this situation. Moreover, the battery was re-charged while the engines worked at their optimal operating points. In this case, the gaps between the generator output power and the load were used to charge the battery. These actions were defined by the optimal power split ratio derived online by the OCS.

Table 2: KPI analysis of simulated vessel performances

KPI	*Conv. vessel using Load following logic*	*Hybrid vessel using RBC (Section 3.4)*	*Vessel using EFCM (Section 3.2)*	*Vessel using OCS*
Total Run Time [hh:mm:ss]	17:30:00	17:30:00	17:30:00	17:30:00
Gen 1 Stop/Start Count [-]	1	3	17	17
Gen 1 Run Time [s]	63000	57240	53400	52500
Gen 2 Stop/Start Count [-]	4	29	31	28
Gen 2 Run Time [s]	36000	25830	18600	16800
SOC Drop Compared to SOC0 [%]	-	12.12	22.70	26.64
Vessel Fuel Used [L]	2541.72	2460.74	2378.01	2364.06
Vessel Fuel Cost [£]	2948.39	2854.46	2758.49	2742.30
Vessel Elec Used [kWh]	-	29.12	54.49	63.93
Vessel Elec Cost [£]	3.21	25.26	39.62	39.21
Vessel Energy Cost [£]	2951.61	2879.71	2798.11	2781.51
Vessel Energy Cost Saved [%]	-	2.44	5.20	5.76
Vessel Energy Cost Saved Compared to RBC [%]	-	-	2.83	3.41
Vessel Energy Cost Saved Compared to EFCM [%]	-	-	-	0.59

To demonstrate the superior performance of the proposed OCS over the comparative energy management schemes, a table of key performance indicators (KPI) was established based on the control design requirements as shown in Table 2. From this table, it is clear that the OCS provided the best fuel economy among the four control strategies under the same load profile. During the 17.5-hour voyage, the proposed OCS managed the battery operation such that the operational time of both the engine-generators was minimised (the first engine had 17 stop-and-start cycles while the second engine had 28) while maintaining the SOC level within its constraint (as shown in the top sub-plot of Figure 8). As a result, the fuel consumption (and therefore CO_2 emissions) was minimised using this control strategy. Compared to the conventional vessel (without a battery) using load following logic, the hybrid vessel using RBC and the hybrid vessel using EFCM, the vessel using OCS could save up to 5.76%, 3.41% and 0.59% energy cost, respectively, under the same working condition. The comparison results therefore confirm that the designed OCS could offer a more fuel-efficient solution for hybrid vessels.

It is recognised that the number of on-off cycles for the engines is much higher than would normally be expected. Presently, standard operation would result in around 4 stop-and-start cycles over this voyage. However, in order to implement hybrid systems to significantly improve efficiency, such as the proposed OCS, vessel operators will need to accept a level of operation that is outside of what they currently consider the norm. The high number of stop-starts may be considered excessive and impact on long term performance, so this needs to be given to a compromised approach to engine stop-starts. The example given here simply demonstrates the level of savings possible if this stop-start regime could be accepted by an operator. It is acknowledged that it is likely that a lower number would be more realistic, compromising between reduced savings and long term impact on engines. The issue of spinning reserve is also another consideration, where the bounds of current power management systems need to be complied with. This may impact how often the proposed OCS can turn engines on and off in order to maintain an allowance for excess capacity to cover potential problems. This can be addressed by maintaining sufficient levels of charge in the batteries to provide reserve combined with further limits on engine on-off times within a specific operating scenario.

5. Conclusion and future work

In this study, the energy management system using the advanced OCS algorithm for hybrid DP vessels was introduced. The OCS has been designed with the smooth combination between the RBC, EFCM and fuzzy gain tuner to provide the optimal operation performance for the vessel, leading to more energy and emission savings. The numerical simulations were performed using Mode-1 of the RT-Sim platform to verify the basic functionalities and effectiveness of the designed OCS. The results show clearly the improved energy performance of the OCS compared to the other energy management strategies.

As future work, the applicability of the OCS in the real system operation environment will be investigated. To enhance this work, Mode-2 of the RT-Sim platform will be used. Furthermore, the limit of engine stop-and-start rate (i.e. per voyage/day) needs to be taken into account when performing the optimisation to minimise its negative impacts on long-term performance and accommodate necessary levels of spinning reserve.

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