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Xie, Peilin; Tan, Sen; Guerrero, Josep M.; Vasquez, Juan C.

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MPC-informed ECMS based real-time power management strategy for hybrid electric ship

Peilin Xie*, Sen Tan, Josep M. Guerrero, Juan C. Vasquez

Aalborg University, Aalborg, 9220, Denmark

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Abstract

Shipboard power systems (SPS) are complex systems connecting multiple power sources, energy storage systems (ESSs) and various types of loads. However, the fluctuated propulsion loads may lead to a low power quality of the system. In this paper, a power management system (PMS) is designed for SPS in the framework of an optimization-based method. With equivalent consumption minimization strategy (ECMS), the proposed method is able to provide an optimal power-split between hybrid energy sources in real time, while minimizing the fuel consumption of the system. Furthermore, the equivalence factor is adjusted by model predictive control (MPC) of PMS. The performances of the proposed approach are evaluated by simulations.

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Keywords: Equivalent consumption minimization strategy; Model predictive control; Power management system; Shipboard power system

1. Introduction

Transportation industry is becoming the foundation of the national economy, where marine transportation takes 80% of the world's trade. Nowadays, diesel generators (DGs) are still the major power source for all maritime applications. Due to the widespread use of fossil fuels, marine fleet becomes a large contributor to greenhouse gasses and emissions. As a result, there is a growing interest towards reducing fuel consumption of the marine vessels [1].

The SPS typically consists of diesel generators, ESSs and various types of loads. However, different from the terrestrial power systems, the fluctuated propulsion loads and pulsed loads are the primary loads in SPSs, which may generate negative effects on the entire power systems [2]. Such load conditions are the key challenges in designing the PMS. Therefore, there is an urgent need to design a reliable power management strategy which can not only manage the power distributions among different power sources in real time, but also reduce fuel consumption [3].

* Corresponding author.
E-mail address: pxi@et.aau.dk (P. Xie).

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The analysis and design of PMS for SPS has been addressed by a considerable amount of literature, which can mainly be classified into rule-based and optimization-based strategies. Although rule-based strategies have the advantage of easy implementation, they may not offer an optimal solution. Optimization-based strategies are widely adopted due to the possibility of providing an optimal or sub-optimal solution to the SPS. A general approach for optimization-based strategies is the loss reduction (LR)-based method, where the PMS aims to reduce the power losses during energy transmissions. However, this method may not guarantee optimal fuel efficiency, because no fuel consumption is considered in this method. ECMS is another technique, whose cost function is constructed by the combination of real fuel consumption and an equivalent fuel consumption regarding to ESS, instantaneously [4].

Taking ECMS into account, the equivalence factor (EF) which converts electrical power consumption into fuel consumption should be considered carefully [5,6]. Most of the research simply considered the EF as a constant [7]. Although easily implemented, it may fail to capture the real transformation relationship between fuel consumption and ESS, thus lead to unsatisfying results. Better performance of ECMS can be achieved by considering a time various EF. However, it should be noted that these approaches require the knowledge of the entire marine load profile, either by historical data or long-term prediction [8]. For systems whose load profile is not known as a priory, MPC is shown to be effective to handle this problem, which enables the PMS to look ahead as far as the established prediction horizons. By applying an ECMS together with MPC, the equivalence factor can be adjusted in real time.

The main objective and contribution of this paper is the analysis and design of a MPC-based power management system for SPS. The proposed PMS is able to supply the high frequency propulsion loads induced by sea wave conditions. With the proposed equivalent consumption minimization strategy, the designed PMS can distribute the power between diesel generators and hybrid ESS with minimum fuel consumption. In addition, the time various equivalence factors are carefully designed with the help of the model predictive control method.

2. SPS description and modeling

In this study, the power system of the electrical ship is composed of a diesel generator, ESS (battery and ultra-capacitor) and propulsion load. An overview of the ship electrical and proposed PMS structure is shown in Fig. 1.

2.1. Modeling of diesel generator

By allowing the generator speed to change within a specific range, an average fuel saving potential in the range of 10% to 20% can be expected [9]. In this paper, a variable-speed diesel generator is utilized to improve fuel efficiency. The characteristics of optimal specific fuel oil consumption (SFOC) and speed are shown in Fig. 2. Considering the low fuel efficiency at low load conditions, it is better for the generator to operate at high load conditions. The generator output power can be expressed as a function of speed by curve fitting,

$$P_{dg} = a_0 + a_1 n_{dg} + a_2 n_{dg}^2 + a_3 n_{dg}^3 \tag{1}$$

where P_{dg} is the output power of the generator, n_{dg} refers to the generator speed, a_0, a_1, a_2 are fixed values.

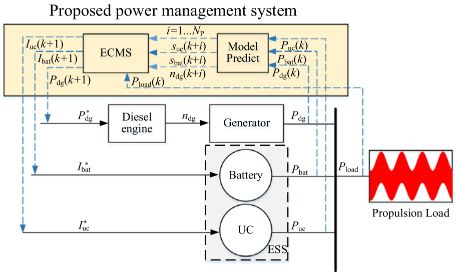

Fig. 1. General structure of the proposed power management system.

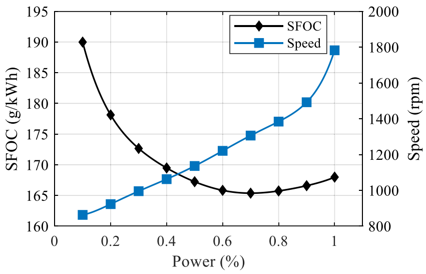

Fig. 2. SFOC and corresponding speed for various output power.

2.2. Hybrid energy storage system

The hybrid energy storage system consists of batteries and ultra-capacitors. The state-space equation of hybrid ESS can be defined as [10]:

$$\begin{bmatrix} \dot{s}_{bat} \\ \dot{s}_{uc} \end{bmatrix} = \begin{bmatrix} 1/3600Q_B & 0 \\ 0 & -1/V_{uc}C \end{bmatrix} \begin{bmatrix} I_{bat} \\ I_{uc} \end{bmatrix} \tag{2}$$

where s_{bat}, s_{uc} are the state of charge (SOC) of the battery and UC, I_{bat} and I_{uc} are the battery and UC currents, Q_B is the capacity of the battery, V_{uc} is the maximum voltage of ultra-capacitor (UC), C_{uc} is the capacitance.

2.3. Propeller and ship hydrodynamic

The propulsion load of the ship can be derived from the propeller model and hydrodynamic model. The propeller thrust T, torque Q and mechanical power P_{load} can be formulated as nonlinear functions of motor shaft speed n, water density ρ and propeller parameters (propeller diameter D), which can be expressed as [1,11].

$$T = sgn(n)\beta\rho n^2 D^4 K_T \tag{3}$$

$$Q = sgn(n)\beta\rho n^2 D^5 K_Q \tag{4}$$

$$P_{load} = 2\pi n Q \tag{5}$$

where K_T and K_Q are thrust and torque coefficients which are determined by advance coefficient, pitch ratio, expanded blade-area ratio and number of blades [12]. β refers to the effects of propeller in-and-out-of water motion and sensitivity to submergence, which can be expressed as [13]:

$$\beta = \begin{cases} 0 & h/D < -0.24 \\ 1 - 0.675 \times (1 - h/D)^{1.258} & -0.24 \le h/D \le 0.65 \\ 1 & h/D > 0.65 \end{cases} \tag{6}$$

where h is the propeller shaft submergence.

The mechanical dynamic of propeller can be described by:

$$m\dot{U} = T(1 - t_d) - (R_F + R_R + R_{wind}) - F \tag{7}$$

where U is the ship speed, m denotes the total mass of ship, t_d is the thrust deduction coefficient. F is the wave disturbance, which is the source of fluctuation load for SPS. R_F, R_R and R_{wind} are ship frictional resistance, wave-making resistance and wind resistance, which can be calculated from [13].

From the propeller and hydrodynamic model, the propulsion load can be captured. In this study, a 10 Hz high-frequency load due to propeller rotation and a 0.1 Hz low-frequency load due to wave disturbance are utilized. The fluctuated propulsion loads serve as power demand for the power management system in Section 3.

3. Power management strategy for AES

The PMS method proposed in this paper is achieved by an optimization method combining the ECMS and MPC strategy to determine the optimal power split between the diesel generator and hybrid ESS. The ECMS is utilized to the minimum fuel consumption and MPC is adopted to perform state predictions and adjust the equivalent factors, as well as control variables in real time.

3.1. ECMS-based optimization problem formulation

The idea of ECMS is to minimize the total equivalent fuel consumption (C), which is described as the sum of generator fuel consumption C_{dg}, converted equivalent fuel consumption from battery (C_{bat}) and UC (C_{uc}):

$$C(t) = C_{dg}(t) + C_{bat}(t) + C_{uc}(t) \tag{8}$$

Considering that the diesel generator consumes real fuel, the instantaneous fuel consumption is given as,

$$C_{dg}(t) = SFOC \cdot \frac{P_{dg}(t)}{\eta_{dg} 3.6 \times 10^6} \tag{9}$$

where η_{dg} is the diesel generator efficiency.

Equivalent fuel consumption of battery and UC can be expressed as follows,

$$C_{bat}(t) = Ef_{bat}(t) \cdot SFOC_{min} \cdot \frac{P_{bat}(t)}{3.6 \times 10^6} \tag{10}$$

$$C_{uc}(t) = Ef_{uc}(t) \cdot SFOC_{min} \cdot \frac{P_{uc}(t)}{3.6 \times 10^6} \tag{11}$$

where $SFOC_{min}$ is set as the minimum value of SFOC in Fig. 2 such that it can encourage the DG to generator more power to ESS and avoid low loading conditions. $Ef_{bat}(t)$ and $Ef_{uc}(t)$ are equivalent factors, which convert electrical powers into equivalent fuel consumption.

The equivalent factor of battery can be derived as [14,15]:

$$Ef_{bat}(t) = \begin{cases} k_{bat}/(\eta_{dg} \times \eta_{chg.av} \times \eta_{dis}) & P_{bat} \geq 0 \\ k_{bat} \times \eta_{dis.av} \times \eta_{chg}/\eta_{dg} & P_{bat} < 0 \end{cases} \tag{12}$$

where k_{bat} is the penalty coefficient of battery. It works to keep the SOC remains at a medium level, which is expressed as:

$$k_{bat} = 1 - \mu \frac{2s_{bat} - (s_{bat(min)} + s_{bat(max)})}{s_{bat(min)} + s_{bat(max)}} \tag{13}$$

where μ is a constant value. $s_{bat(min)}$ and $s_{bat(max)}$ represent the minimum and maximum SOC of battery. $\eta_{chg.av}$ and $\eta_{dis.av}$ are constant values, which refer to the average efficiencies of battery during charging and discharging mode, respectively. η_{chg} and η_{dis} are the real-time efficiencies, which can be derived as nonlinear functions of battery power P_{bat} and s_{bat}. The relationship of η_{chg} and η_{dis} versus P_{bat} and s_{bat} are expressed in [14].

The equivalent factor of UC can be derived as:

$$Ef_{uc}(t) = \begin{cases} k_{uc}/(\eta_{dg} \times \eta_{uc}) & P_{uc} \geq 0 \\ k_{uc} \times \eta_{uc}/\eta_{dg} & P_{uc} < 0 \end{cases} \tag{14}$$

where k_{uc} is the penalty coefficient of UC, which holds the same equation as (13), expecting that parameters are adjusted to UC parameters. η_{uc} refers to the efficiency of UC, calculated by:

$$\eta_{uc} = (2^{\alpha} - 1)^2 \tag{15}$$

where α is the fractional-order related to the dispersion coefficient of the electrode [16], assumed to be 0.9 in this paper. From the above analysis, the total equivalent fuel consumption can be obtained instantaneously and will be used for further power management process.

3.2. MPC-informed ECMS power management strategy

MPC is adopted to compensate for the fluctuated load based on the discretized model. The discrete system model of PMS can be obtained from (1) and (2) as:

$$x(k + N_p) = f(x(k), u(k + 1), u(k + 2), \ldots, u(k + N_c)) \tag{16}$$

where $x(k)^T = [P_{dg}(k), s_{bat}(k), s_{uc}(k)]^T$ denotes the state variables, $u(k)^T = [n_{dg}(k), I_{bat}(k), I_{uc}(k)]^T$ denotes the control inputs, N_p is the prediction horizon and N_c is the control horizon.

In order to reduce total fuel consumption, the optimization problem is formulated as:

$$\begin{aligned} &\min_{u(k)} \quad J = \sum_{k=1}^{N_p} C(t_k) \\ &s.t. \begin{cases} P_{dg}(k) + P_{bat}(k) + P_{uc}(k) = P_{load} \\ n_{dg}(k) \in [n_{dg(min)}, n_{dg(max)}] \\ I_{bat,uc}(k) \in [I_{bat,uc(min)}, I_{bat,uc(max)}] \\ s_{bat,uc}(k) \in [s_{bat,uc(min)}, s_{bat,uc(max)}] \end{cases} \end{aligned} \tag{17}$$

Fig. 1 shows the control structure of the proposed power management strategy. As shown in Fig. 1, the system performance is first evaluated by groups of future system outputs predicted by MPC. In addition to that, the equivalent factors which vary with system states are also adjusted. Then, the optimal control inputs are obtained to minimize the fuel consumption after comparing the cost function. Finally, the first control input $u(k)$ is fed into PMS to achieve the power tracking as well as compensate for the fluctuated propulsion load.

4. Simulation results

In order to evaluate the performance of the proposed ECMS in this study, simulations results are provided considering a hybrid all-electric shipboard power system. Traditional LR-based method is used as a benchmark here. The system considered in this case mainly consists of a diesel generator, 10 sets of batteries, 10 sets of ultra-capacitors and propulsion load. The DG is the main power source which is responsible for supplying the propulsion load. The battery sets are used as the main energy storage source. The UC sets are utilized to compensate for the high frequency load induced by propeller rotation. The parameters of each power module are listed in Table 1. The control period is 0.01 s in the simulation.

Table 1. Electrical parameters.

Modules	Parameters	Symbol	Values
Diesel generator	Rated power	P^*_{dg}	2 MW
	Efficiency	η_{dg}	96%
	Rated power	P^*_{bat}	25.6 kW
Battery	Capacity	Q	100 Ah
	SOC range	$s_{bat(min),(max)}$	0.2, 0.9
	Initial SOC	s_{init}	0.5
Ultra-capacitor	Rated power	P^*_{uc}	25 kW
	Capacitance	C_{uc}	63 F
	Resistance	R_{uc}	6.8 mΩ
	SOC range	$s_{uc(min),(max)}$	0.2, 0.9
	Initial SOC	s_{init}	0.5

4.1. *Effectiveness validation*

In order to demonstrate the superiority of the proposed method, studies in this section investigate the performance of PMS under a large range of load conditions. In this case, the ship speed rises from 0 to 7 knots within 460 s. Fig. 3 shows the power tracking and output power of UC, battery and DG for this case.

Concluded from Fig. 3 that there is a good power tracking performance during operations, and DG is constantly charging the battery from 0 s to 190 s at low load range. Due to the lower fuel efficiency at low loads, the ECMS is trying to increase the DG load by charging the battery. After 190 s, the battery sets start to supply power to the system. In addition, it can be seen that the UC is able to provide a high frequency power to meet the high frequency load. Therefore, the proposed strategy could meet the demand of shipboard power system.

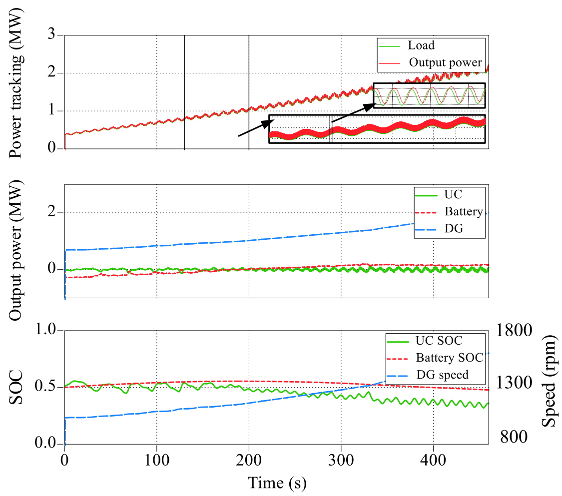

Fig. 3. Power tracking.

4.2. Fuel savings ability

In order to assess the performance of the ECMS in terms of its fuel savings ability, this study compares the actual fuel consumption of the system between proposed ECMS and LR method under variable speed and fix speed

Table 2. Fuel consumption.

Speed mode	Method	Fuel consumption (kg)			
		3 knots	5 knots	5.5 knots	6.2 knots
Variable speed	ECMS	26.67	54.81	62.73	79.88
	LR	26.72	55.17	62.78	80.37
Fix speed	ECMS	27.08	55.89	64.04	83.43
	LR	27.23	56.20	64.26	83.52

Table 3. Final battery SOC.

Method	Final battery SOC			
	3 knots	5 knots	5.5 knots	6.2 knots
ECMS	0.5855	0.5045	0.5405	0.5270
LR	0.4865	0.4910	0.4820	0.4955

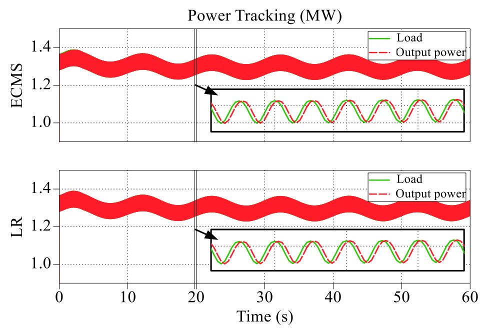

Fig. 4. Power tracking under ECMS and LR methods.

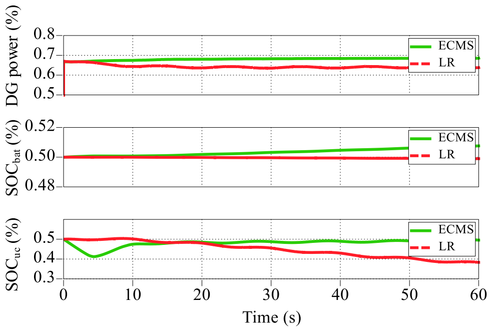

Fig. 5. Comparison of DG output power, battery SOC and UC SOC.

modes. In this case, the ship runs for 15 min at the speed of 3 knots, 5 knots, 5.5 knots and 6.2 knots, respectively. The cumulative fuel consumption and savings of system are given in Table 2.

Concluded from Table 2 that the proposed ECMS can achieve good fuel savings compared to LR method, especially in high ship speed. Moreover, it can be observed that the variable speed mode performs better than the fix speed mode. In order to make a fair comparison of fuel consumption, the final battery SOC under variable speed mode are given in Table 3. It can be observed that although the fuel savings are comparatively small for the proposed ECMS method in variable speed mode, more energy is flowed into the battery. Figs. 4 and 5 give a comparison of power tracking and UC, battery SOC between ECMS and LR method at the speed of 3 knots. As seen from Fig. 4 that both methods can achieve a good power tracking performance. It can be observed from Fig. 5 that ECMS can guarantee the DG works on high fuel efficiency points and charges the battery and UC during operations. However, the LR aims to reduce the DG output power to minimize power losses. It can be concluded that the ECMS can, on one hand, generate more power and on the other hand, use fewer fuels. Furthermore, the output power of DG that a 7.9% fuel saving is achieved by ECMS. Therefore, the proposed ECMS could guarantee the economy of fuel.

5. Conclusion

This paper presents an optimization-based real-time power management strategy for all electrical DC ship, powered by hybrid energy sources (variable-speed diesel generator, battery and ultra-capacitor). Based on the equivalent consumption minimization strategy, the proposed strategy can provide a better performance of minimizing fuel consumption and real-time load tracking under fluctuated propulsion loads compared with traditional methods. Model predictive control is utilized for state prediction. Comprehensive simulations are presented to illustrate the effectiveness and achievable performance of the proposed power management system. Future work will focus on the implementation of the proposed PMS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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