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Scheduling of Power Generation in Hybrid Shipboard Microgrids with Energy Storage Systems

Muzaidi Othman^{1,2}, Amjad Anvari-Moghaddam¹, Norbaizura Ahamad^{1,2}, Su, Chun-Lien³, Josep M. Guerrero¹

¹Department of Energy Technology, Aalborg University, Aalborg, Denmark

²Universiti Malaysia Perlis, Malaysia

³National Kaohsiung Marine University, Taiwan

Email: mum@et.aau.dk

Abstract— Concerns about the impact of global warming caused by air pollution and depletion of fossil fuels have attracted attention and opportunities in transportation especially in maritime industry. In all electric ships, the electrical equipment including electric propulsion is connected to the common ship electrical network to achieve better fuel consumption with less emission. However, the low-load factor of the parallel diesel generators (DGs) in some operating conditions, can negatively affect the fuel consumption rate. As an alternative, two or more power sources such as batteries and renewable-based prime movers can be integrated into the system aboard to improve the overall system performance. By optimal scheduling of the power sources, poor low-load efficiency can be avoided and controllable units can be dispatched in an emission-aware and cost-effective manner. This paper analyzes how much the operating cost of a shipboard system can be improved (based on estimation of specific fuel consumption (SFC) curve of a real system) considering the dynamic load profile with and without energy storage systems (ESSs). The case study in this paper is a ferry with a conversion from traditional diesel mechanical power to electrical propulsion powered by DGs and ESSs.

Keywords—Hybrid shipboard; microgrid; ESS; energy scheduling; power management.

I. INTRODUCTION

Concern about air quality and fuel cost have created opportunities in different research areas, especially in transportation industry. In maritime transportation, there are strict regulations imposed by the maritime authorities regarding emission resulted from the fuel combustion engines such as CO₂, SO_x and NO_x. With this regard, several technological improvements have to put in place such as on-board electrification. Electrification in marine vessel offers the potential of fuel and emission reduction. It is because the use of so-called Integrated Power System (IPS) concept, where electric propulsion and ship services are connected into a common electrical platform, thus avoiding a conventional system of separate generation for these loads [1]. IPS also offers plug and play capabilities for alternative energy sources and scheduling of several sources such as renewable energy and energy storage system (ESS) in a distributed fashion similar to a stand-alone microgrid. With the advancement of ESS technology today, it is possible to achieve better fuel economy and move towards safer and greener marine vessels.

This is evident by the success of hybrid electric vehicles (HEVs) on roads that have a long history of involving the use of various energy storage architectures. In fact, vessels can benefit from more space for the ESS as compared to HEVs. However, the hybrid ship market is much smaller than HEVs and only available for limited sea-travel range. On shipboard, ESS has its role as energy backup and can also avoid oversizing of the DG to meet the peak demand of the ship. In addition, ESS could pick up the load during load shifting much faster than a DG with slower response and voltage/frequency regulation capability [2]. As for fuel economy, the hybrid onboard architectures with ESS can support the DG or can alternately operate with DG to serve the load. Thus, it can also reduce the maintenance cost based on DG operation time. The feasible study of hybrid electric transportation ship as a conversion from the diesel operated can be find in [3]. In [4], the example of operational prototype of a hybrid ship for the coastal fishing ship is shown where it equipped with 190 kWh battery packs. In [5], the combinations of battery and super capacitor are investigated in excursion ship to achieve more efficient power from the ESSs. All these example is using serial hybrid electric power system.

By the use of ESS aboard, DGs can be dispatched in a way to share the load proportionally while being operated at (or near) maximum-efficiency point. In this perspective, ESSs act as back-up units that not-only energize the platform during the peak-load periods with lower costs and improve the dynamic behavior of the system, but also help reduction of pollutant emissions through avoiding unnecessary conventional unit commitments [6]. The energy management of on-board hybrid power system with energy storage are discussed in [7]-[11]. In economic point of view, several DG can be operated based on economic dispatch to find the optimal point for each of the DG [7]. In [8] mathematical approaches have been used in optimizing the hybrid energy in shipboard. Studies in [9]-[13] show the operation of hybrid ship with ESS and PV's based on economic objectives. authors of [14] also investigate optimal scheduling of a shipboard system based on accurate estimation of specific fuel consumption (SFC) of diesel-generators.

The purpose of this paper is to study the operation management problem of a real electric ship integrated with ESS to reduce fuel consumption and emission from the diesel

generators. To this end, different operating conditions are considered and the proposed optimal scheduling model is tested in these conditions against the existing rule-based (logic) scheduling methods. Finally a comparison is made among different models in terms of fuel consumption and cost effectiveness.

This paper is organized as follows. In Section II, the under-study system and its specifications are described. Section III, formulates the optimal scheduling model of the examined system. Simulation results in different scenarios are presented in Section IV. Finally, Section V concludes the paper.

II. SYSTEM UNDER STUDY

The ship under study is a small ferry used for transportation from point A to B in the route shown in Fig.1. The travel time is 5 minutes at a speed of 5-9 knot (9.2-16.7 km/h) and waiting time at each station is 5 minutes. Total time for a complete journey is 15 minutes. The ferry has two diesel generators (DGs) with a rated power of 100 kVA each.



Figure 1. Gushan Ferry Pier Station (Point A) to Cijin Ferry Station (Point B) ferry route.

The examined ferry is a hybrid AC/DC electric system with a single line diagram shown in Fig. 2. Two generators are connected to the common AC bus. The load sharing will be achieved by controlling the speed of DGs through governors. Hotel loads are served at the AC bus through the 440/220V step-down transformer. Bidirectional AC/DC converters are used to connect the AC bus to a 750V DC bus feeding both ESS and the propulsion motor through dedicated DC/DC converters and adjustable speed drives, respectively. Table I shows the parameters of the practical ferry under study.

TABLE I. FERRY PARAMETERS

Component	Parameter
Diesel	2 x (P_{mech} : 92 kW, P_{elect} : 105 kVA, 84 kW (0.8 pf))
Generator (DG)	440 VAC, 60 Hz
ESS	650 V, 100 kWh (50 x 13.2 V, 160 Ah)
Hotel load	35 kW- max (total connected load)
Propulsion load	300 kW – max
Distance travel	650 meters for one way
Time travel	5 minutes Cruise at 5 knot
Waiting time	5 minutes at each port
Top speed	10 knot
Weight	96 Tonnes
Length	22.5 m

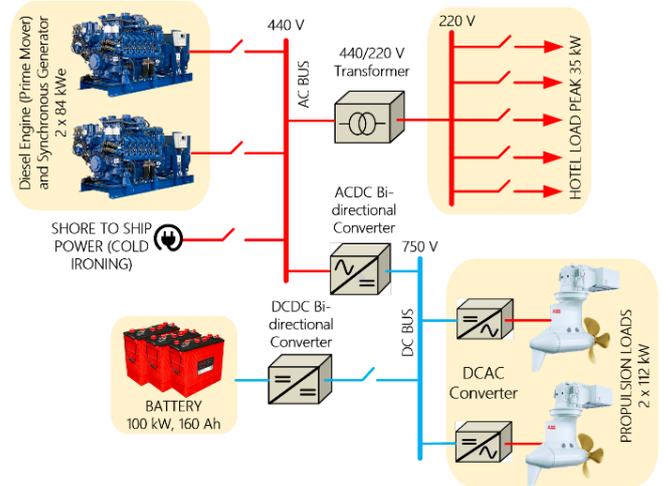


Figure 2. Hybrid AC/DC Shipboard Power System in practical ferry

A. Diesel Generator

The main generation of this ferry is based on diesel engines, which rated 92 kW of mechanical power each (Table I). It can be operated either 50 or 60 Hz of frequency with a speed of 1500 rpm or 1800 rpm, respectively. The information of the DG used can be find in [15]. To meet the load of the ship, the DG's are connected in parallel so that the loads can be shared based on a droop or isochronous control mode [16]. DGs in the ship are sized accordingly so that they could meet the peak load regardless of existence of other energy sources such as ESSs.

The fuel consumption of the diesel engine is given by a specific fuel consumption (SFC) which expressed in g/kWh . The hourly fuel consumption curve of DG regardless of DG speed, can be approximate by a quadratic function as in (1) [17]. Figure 3 shows the approximation of the SFC versus mechanical power of individual DG. The total fuel consumption of the individual diesel engines over the examined period can be obtained by (2).

$$SFC(P_m) = c_0 + aP_m + bP_m^2 \quad (1)$$

$$FC_{tot} = \sum_{j=1}^n (SFC(P_{m,j}) \times P_{m,j} \times \Delta t) \quad (2)$$

where P_m is the mechanical power, c_0 , a and b are coefficient of the second-order polynomial SFC function. FC_{tot} is the total fuel consumption in *gram* for n^{th} DG. Most of the DGs deliver optimal power at lower SFC if working at a loading condition between 70 – 90% [17]. DG fuel consumption can also be estimated by using fuel consumption graph in $l[18]/hr$ unit as provided by manufactures [18].

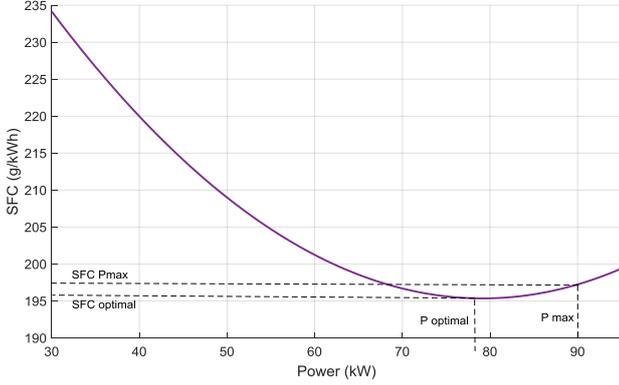


Figure 3. Estimation of the SFC curve of the generator

Although SFC curve is based on mechanical power, P_m , the electrical power, P_e , can be calculated based on relation in (3). η_{conv} is the efficiency of synchronous generator conversion from mechanical power to electrical power. This conversion parameter can be found in DG’s datasheet [15].

$$P_e = \eta_{conv} \times P_m \quad (3)$$

Efficiency of DG, η_{DG} is given by the relationship between load factor, DL and specific operating power factor, h_{pf} as written in (4). DL is the ratio between output electrical power, P_e and rated power, P_{dg} of the DG as written in (5) [18]:

$$\eta_{DG} = h_{pf} \times DL \quad (4)$$

$$DL = \frac{P_e}{P_{dg}} \times 100 \quad (5)$$

B. Energy Storage System (ESS)

The ESS technology considered in this study is a Lithium Iron Phosphate (LiFePO₄) which is based on Li-Ion technology. The ESS is composed of 50 units in series to achieve the required voltage. To prolong the battery life, the depth of discharge (DOD) is limited to 60%. Also slower charging rates (e.g. at C/3) could also be adopted to prolong the battery life as suggested by the manufacturer. However, for an off-grid diesel-battery power system, lower DOD will result in more fuel consumption. Therefore there will be a tradeoff between fuel consumption and DOD of the batteries [19]. The ESS data is given in Table II and the technical specifications are given in [20]. SOC of the battery at time t ,

considering a charging/discharging process during interval time, Δt is given by (6):

$$SOC(t)_{ch/dch} = \begin{cases} SOC(t-1)_{ch} + [\eta_{ch} \times P_{ch}(t) \times \Delta t] & ; Charge \\ SOC(t-1)_{dch} - \left[\frac{1}{\eta_{dch}} \times P_{dch}(t) \times \Delta t \right] & ; Discharge \end{cases} \quad (6)$$

where, $SOC_{ch/dch}$, $\eta_{ch/dch}$, Δt is the state of charge/discharge of the battery, charge/discharge efficiency and the time interval for charging/discharging. In a rule-based power management strategy, the operation of DGs is based on the battery SOC level. DGs will turn OFF when the batteries are charged till the SOC of 80%. At this level, the ESS is used to serve the propulsion and the hotel loads until the lower SOC bound of 20%. When SOC reaches 20%, DGs are dispatched again to serve the loads and charge the batteries.

TABLE II. BATTERY DATA (LIFEPO4)

Capacity (Ah)	160
Nominal Voltage (V)	13.2
Charge current (A)	160 (1C)
Charge current (A) for endurance (cycle life)	52.8 (C/3)
Discharge current (A)	480 A (3C)
Discharge current (A) for endurance (cycle life)	52.8 (C/3)

C. Load

Based on Table I, the maximum demand for propulsion and hotel loads is 300 kW and 35 kW, respectively. However, the propulsion load depends on the ship speed given in Table III; i.e., the propulsion power varies according to the required speed during travel time. Hotel load consists of the electrical demand for ship’s control panel, air conditioning, lighting, electric pumps and so on.

The total load demand can be represented in shape of a chronological load curve over specific time horizon [7]. The total operation time of the ship per one day is 20 hours. For simplicity, the load profile of the ship is divided into 20 intervals each with a power level equal to the average power, P_D during 1 hour operation as shown in (7).

$$\int_{t_{j-1}}^{t_j} P_D(t).dt = P_D(j).\Delta T(j); \quad \forall j = 1, 2, \dots, n \quad (7)$$

TABLE III. RELATION OF FERRY SPEED AND POWER CONSUMPTION OF PROPULSION UNIT

Speed (knots)	5	6	7	8
Power Consumption (kW)	40	60	90	150

D. Modes of operation

The ferry modes of operation are classified in Table IV and depicted in fig. 4. As mentioned before, the SOC level of the ESS triggers mode change during the operation horizon.

TABLE IV. FERRY MODES OF OPERATION

Mode	Description				
	DG 1	DG 2	Battery	Propulsion	Hotel load
1	OFF	OFF	Discharge		
2	ON	OFF	Charging	ON*/OFF**	
3	ON	ON	Charging		ON
4	ON	OFF	Discharge		
5	OFF	OFF	Charging	OFF**	

* Sailing, ** Berthing

Mode 1: Also called fully electric mode where the propulsion and hotel loads are powered by the ESS. The battery-based ESS is discharged with a planned DOD of 60%, meaning that the SOC will gradually decrease from 80% to 20%. During this time, DGs are OFF.

$$P_{bat,dch}(t) = P_{prop}(t) + P_{hotel}(t) \quad (8)$$

Mode 2: When the SOC level drops to 20%, one DG will be turned ON and start charging the ESS while serving the propulsion and hotel loads as follows:

$$P_{dg1}(t) = P_{prop}(t) + P_{hotel}(t) + P_{bat,ch}(t) \quad (9)$$

Mode 3: When high power is required during peak-time and the $SOC \leq 20\%$, both DGs will be turned ON and start charging the ESS:

$$P_{dg1}(t) + P_{dg2}(t) = P_{prop}(t) + P_{hotel}(t) + P_{bat,ch}(t) \quad (10)$$

Mode 4: When high power is required during peak-time and the $SOC \geq 20\%$, one DG will be dispatched and the battery will support the power required to avoid low-load factor due to the commitment of the second DG :

$$P_{dg1}(t) + P_{bat,dch}(t) = P_{prop}(t) + P_{hotel}(t) \quad (11)$$

Mode 5: When Shore Power Supply (SPS) is available (during berthing) and the battery $SOC \leq 20\%$, all DGs and propulsion loads will be turned OFF and the SPS will serve the hotel loads while charging the ESS aboard:

$$P_{SPS}(t) = P_{bat,ch}(t) + P_{hotel}(t) \quad (12)$$

where $P_{dg1/dg2}$, P_{prop} , P_{hotel} , $P_{bat,ch/dch}$, P_{ops} are the DG 1 and 2 electric output power, propulsion load, hotel load, battery charge/discharge power and SPS power.

In modes 2 to 4, the generators will be operated at the optimal point of SFC curve which is normally located at a 70-90% load factor. Thus, in modes 2 and 3, the power to charge the batteries are based on energy balance equations presented in (9)-(10) and the maximum efficiency of the DGs. However, the rate of charge power is controlled using DC/DC bidirectional converters. Figure 5 shows the flow

chart of the ship operation based on if-else statements or a so-called rule-based/logic algorithm.

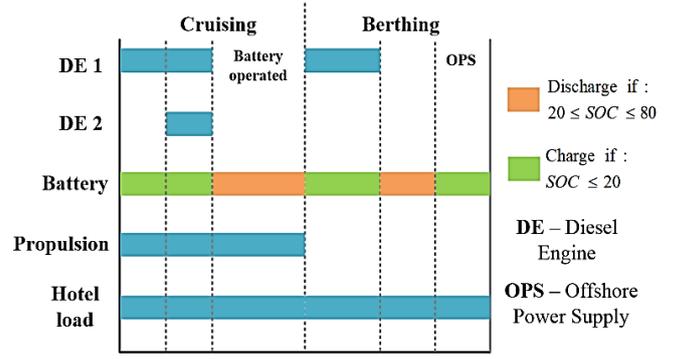


Figure 4. Possible modes of operation during cruising and berthing

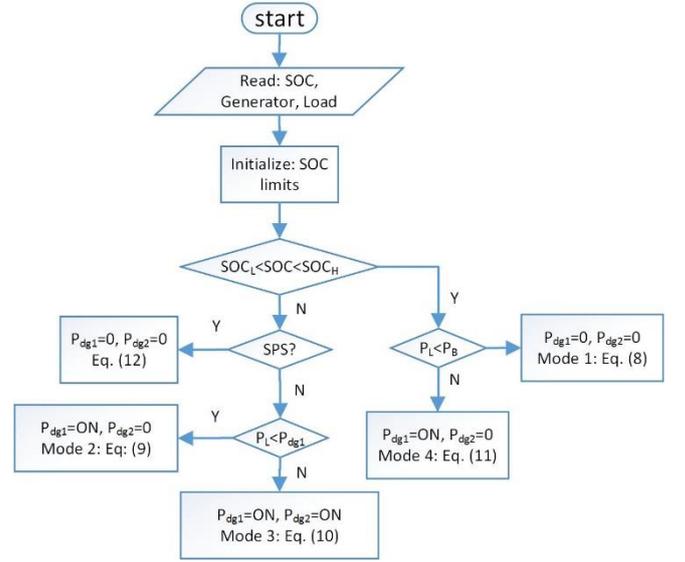


Figure 5. Flow chart of operation based of if-else statements

III. OPTIMAL SCHEDULING OF THE SHIPBOARD SYSTEM

In this section, the optimal scheduling of the examined shipboard system is presented. The scheduling problem is formulated as a mixed-integer non-linear programming (MINLP) model with an economic objective and several technical constraints.

a. Objective Function

The generation side scheduling problem is formulated as a deterministic optimization problem where the objective is defined as minimizing the fuel consumption cost of the system over the study period:

$$\text{COST} = \min \sum_{t=1}^T \sum_{i=1}^N (0.006P_{m,i,t}^3 - 1.35P_{m,i,t}^2 + 300P_{m,i,t}) \Delta T_t \quad (13)$$

b. Constraints

The constraints of this optimization problem ensure that the optimal solutions are found within the feasible operation region.

- *Energy balance:*

$$\sum_{i=1}^N P_{gen,i} + P_{dch}(t) = P_{load}(t) + P_{ch}(t) \quad \forall t \in T \quad (14)$$

$$P_{gen,i}(t) = P_{m,i}(t) \times \eta_{conv} \times h_{pf} \quad (15)$$

$$P_{gen,i,min} \leq P_{gen,i}(t) \leq P_{gen,i,max} \quad (16)$$

- *Energy Storage System:*

The amount of available energy in the ESS can be estimated based on (6). However, the upper and the lower boundary for charging and discharging power of the system as well the system capacity are considered as in (17)-(19):

$$P_{ch,min} \times (1-u(t)) \leq P_{ch}(t) \leq P_{ch,max} \times (1-u(t)) \quad (17)$$

$$P_{dch,min} \times u(t) \leq P_{dch}(t) \leq P_{dch,max} \times u(t)$$

$$P_{dch,min} = 0.2 \times SOC_{max} ; P_{dch,max} = 0.8 \times SOC_{max} \quad (18)$$

$$SOC_{max} = 104kW ; SOC_{min} = 0 \quad (19)$$

Note that $p_{ch/dch}(t)$ is determine by control parameter of $u(t)$ in (17), where $u(t)=1$ denotes discharging, and $u(t)=0$ shows charging process.

IV. RESULTS AND DISCUSSIONS

This section presents the simulation results for two different case studies: the conventional operating mode governed through a logic controller as discussed in section II, and the optimal operating mode as proposed in section III. For the conventional operating mode, the load factor of the DGs is selected by the controller to be in the range of 70-90% as recommended by the manufacturer. For the optimal operating mode, the cost curve of the generating units, as tabulated in Table V, are considered for selection of the loading level. The ship load profile together with dispatch of units are visualized in Figs. 6 and 7 for the conventional and the optimal operating mode, respectively. The fuel consumption in kg, is also calculated and presented in Table VI for 3 different cases: without battery (in non-optimized case), with battery (in non-optimized case) and with battery (in optimized case).

TABLE V. COST COEFFICIENT OF THE GENERATORS

Cost coefficients (gr/h)					
a_1 (g/kw ³)	b_1 (g/kw ²)	c_1 (g/kw)	a_2 (g/kw ³)	b_2 (g/kw ²)	c_2 (g/kw)
0.006	-1.35	300	0.006	-1.35	300

For non-optimal case as depicted in Figure 6, a fixed power output of 75 kW is selected for each DG which reflects a load factor around 83.3%. In this value, it is assumed that the generator has the optimal SFC. For the optimal scheduling case, the algorithm as described in section III is applied to determine the economic dispatch of the units based on different loading conditions and the battery SOC. As can be seen from the results in Figure 7, the output power of DG units is determined as 72.55 kW, which is consistent with the optimal loading conditions and reduced fuel consumption rates. The total DG fuel consumption are summarized in Table VI.

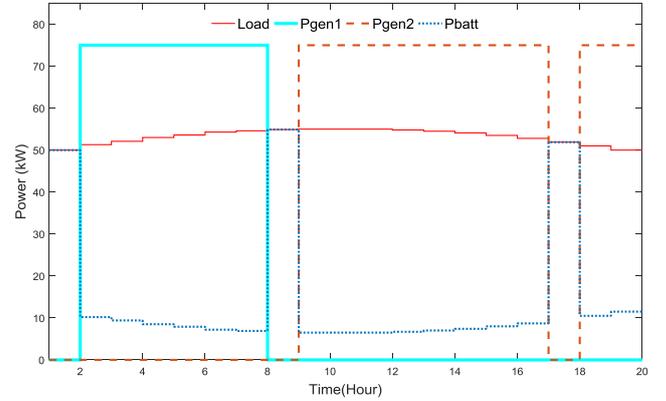


Figure 6. Rule-based scheduling of the shipboard power system (conventional operating mode)

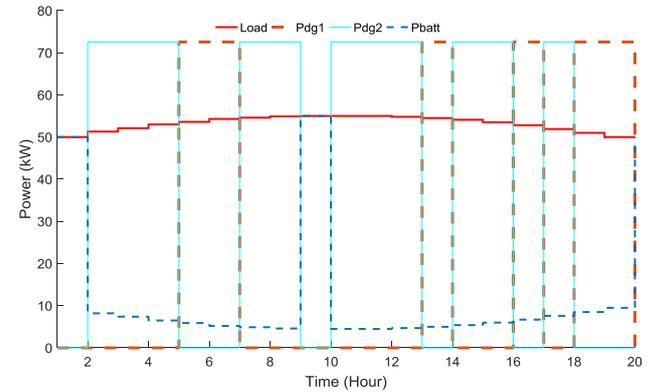


Figure 7. Optimal scheduling of the shipboard power system

TABLE VI. COMPARISON OF FUEL CONSUMPTION WITH AND WITHOUT BATTERY-BASED ESS

	Without battery	With battery	With battery and optimized
Scheduling	1 DG	2 DG	2 DG
Power generated by DG	Based on load profile	75 kW (Fixed power)	72.6 kW (optimized)
Load factor (%) (eq. 5)	67.8 – 74.5	83.3	80.7
DG FC (kg)	260.29	296.44	245.27

V. CONCLUSION

This paper presented different scheduling models of a shipboard system supported by energy storage devices. A rule-based algorithm and an optimal scheduling procedure were presented for operation management of a ferry in a typical journey which takes couple of minutes and repeated several times a day. Simulation results demonstrated that by optimal scheduling of the power sources aboard, poor low-load efficiency conditions can be avoided, controllable units can be dispatched in an emission-aware and cost-effective way and energy storage systems could help reaching better performance in terms of cost, lifetime and flexibility.

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