Optimal Active Power Management in All Electric Ship employing DC Grid technology

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Abstract

Extensive electrification and the use of dc distribution grid are recently proved to be very promising technologies for the development of more efficient and environmentally friendly ships. Onboard dc grids present several advantages such as, improved efficiency, easy integration of different types of power sources, reduced size and rating of switchboard, elimination of reactive power flow, increased reconfiguration capability etc. All electric ship (AES) concept, dc distribution grid and optimal power management can lead to a substantial improvement of ship efficiency and compliance with the environmental constraints. In this paper, a method for optimal demand side management and power generation scheduling is proposed for AES employing dc grid. Demand side management is based on the adjustment of the power consumed by ship electric propulsion motors. Dynamic programming algorithm subject to operation, environmental and travel constraints is used to solve the above problem.

KEYWORDS

All electric ship, dynamic programming, GHG emissions limitation, onboard DC grids, optimal power management.

1. INTRODUCTION

The need for more efficient ships has led to efforts to improve the efficiency of all ship energy subsystems. Several studies have shown that the extensive electrification of ship power systems, known as All Electric Ship (AES) if electric propulsion motors are used, can lead to a “greener” and more efficient ship. To this end, novel concepts are explored, with an attractive one being the introduction of direct current (DC) in the power distribution system. Onboard DC grids present several advantages [1] such as, improved efficiency, easy integration of different types of power sources, reduced size and rating of switchboard, elimination of reactive power flow, increased reconfiguration capability etc. Ship efficiency is improved mainly by the fact that the power generation system is not locked at a specific frequency while space savings and weight reduction have also a significant positive effect. The vast majority of ship electric generators prime movers are combustion engines, most fueled with liquid oil, some with liquid natural gas while some can use both liquid fuel and gas. Prime mover fixed speed operation in conventional ship power systems entails minimum fuel consumption within a narrow operating area (usually around 85% of nominal power). In case of dc grid technology variable speed operation is possible and minimum fuel consumption can be obtained in a wider operating area while fuel consumption is significantly decreased as compared with fixed speed operation. Variable speed operation is especially beneficial for vessels with highly variable load like those with dynamic positioning operation capability.

Further improvement in ship power system efficiency could be achieved if optimal power management and control techniques are adopted [2]. Except from the maximization of ship energy efficiency another crucial issue for the future ship power systems is the limitation of greenhouse gas (GHG) emissions. However, AES is a very complex system making the application of centralized optimal control systems quite difficult and challenging. Optimal power management in AES is a complex optimization problem, since next to the minimization of the operational cost and GHG emissions, several technical and operational constraints, like power production ramp rates, minimum–maximum power production, minimum generator operation time, ship speed limits, total route length, constraints stemming from calls at intermediate ports etc., must be satisfied. Moreover, several of the optimization goals might not be compatible with each other, while the problems of demand side management and power generation scheduling are coupled and cannot be solved independently.

This paper aims to present in a coherent and methodical way an optimal active power management technique that could be applied to AES employing dc grids leading to the improvement of ship efficiency and the limitation of GHG emissions.

2. AES POWER SYSTEM

A generic single-line diagram of an AES with dc distribution grid is shown in Fig. 1. Electric power generation system supplies ship service load and the electric propulsion motors. The new concept in this type of ship power system is that the power produced by the generators if fed by ac-dc power converters to the dc distribution grid while dc-ac converters are used where power should be supplied to ac loads.

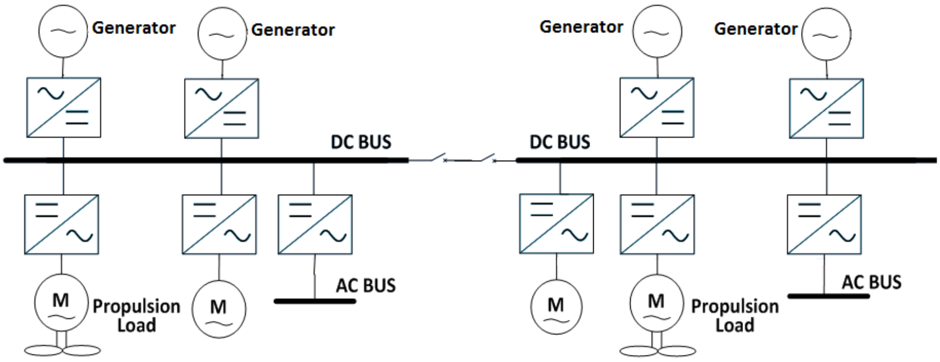


Figure 1. Generic single-line diagram of AES

2.1 Operation Constraints in AES Power System Operation

AES power system operation is subject to constraints stemming from power generation-consumption balance, generator loading, ramp rate limitation, blackout prevention and generator frequent start/stop avoidance. There are also some additional constraints related with ship operation listed next,

- Ship speed is upper and lower bounded by the respective maximum and minimum ship speed.
- The distance traveled by the ship when arriving at intermediate ports should be equal to the route length between ship departure port and the intermediate port.
- The distance traveled at the end of the last time interval of the optimization period should be equal to the total route length.
- GHG emissions should be limited below a certain upper limit.

2.2 Economic and environmentally friendly AES operation

AES load is composed by ship service and electric propulsion load. Electric propulsion load includes propulsion and thruster drives while ship service load comprises the remaining part of the electric power consumption.

$$L = P_{\mathrm{Pr}op} + L_{Serv} \tag{1}$$

The flexibility of the electric load depends highly on the flexibility of the power demand of the electric propulsion motors. Propulsion power depends on ship speed which is in turn derived by travel scheduling. Ship electric propulsion system power demand can be adjusted with respect to ship service load in order to lead to more economic and environmentally friendly operation.

Specific fuel consumption function (*SFC*) is particularly useful for the determination of the most economical point of operation of a generator. *SFC* determines generator fuel consumption per MW and hour and it can be approximated as follows:

$$SFC_i(P_i,\omega^*) = \frac{a_{0i} + a_{1i} \cdot P_i(\omega^*) + a_{2i} \cdot P_i^2(\omega^*)}{P_i(\omega^*)}, \qquad P_{\min,i} \le P_i \le P_{\max,i} \tag{2}$$

Where, P_i is the power produced by i-th generator and ω^* is the optimal rotating speed of the generator prime mover. In ship power systems with dc grid technology ω^* is not constant but it is continuously adjusted.

In the following analysis it is assumed that speed controller ensures successful tracking of optimal speed ω^* and the steady state operation is considered where *SFC* is decoupled from ω^*. However, it is noted that the shape of *SFC* curve of a variable speed engine is different from that of the respective fixed speed engine. In the case study presented in section 4 typical *SFC* curves of variable speed engines are used. In case of variable speed operation minimum fuel consumption can be obtained in a wider operating area while fuel consumption is significantly decreased as compared with fixed speed operation.

The total variable operation cost, *ToC,* of AES power system for a travel time period *T*, is calculated as:

$$\mathrm{To}C = \sum_{j=1}^{T} \sum_{i=1}^{N_g} \left(St_{ij} \cdot \left(Fuel\_Cost_i \cdot SFC_i(P_{ij}) + OC_i \right) \cdot P_{ij} \cdot \Delta T_j + SC_{ij} \right) \tag{3}$$

Where, OC_i is the variable operation cost per produced MWh including lubricants, maintenance etc., SC_{ij} is the start-up cost of the i-th generator at time interval, ΔT_j, $Fuel\_Cost_i$ is the unit cost of the fuel consumed by the i-th generator (m.u./fuel gram) and St_{ij} is a parameter being equal to 1 or 0 if the i-th unit is ON or OFF, respectively.

According to the International Maritime Organization policy ship operation efficiency should be evaluated via Energy Efficiency Operation Indicator (EEOI). EEOI can be slightly modified to facilitate the optimization of AES operation if it is referred to an arbitrary observation time interval ΔT_j, as follows:

$$\mathrm{EEOI}_{1,j} = \frac{mCO_2}{LF \cdot V_j \cdot \Delta T_j} = \frac{\sum_i c_i \cdot P_{ij} \cdot SFC_i(P_{ij})}{LF \cdot V_j} \quad \left[{gCO_2}/{tn \cdot kn} \right] \tag{4}$$

Ship loading factor, *LF,* is calculated as [3]:

$$LF = \frac{n'_P \cdot 0.1 + n'_V}{n_P \cdot 0.1 + n_V} GT \tag{5}$$

Where, GT is ship gross tonnage, n'_V is the number of vehicles onboard, n_V is the maximum number of vehicles, n'_P is the number of passengers onboard and n_P is the maximum number of passengers.

2.3 Propulsion load adjustment

Ship speed-propulsion power curve depends on hull resistance at specific conditions (loading of the ship, weather conditions etc.) and it is well-described by the following formula [4]:

$$P_{Prop} = c_{P1} \cdot V^{c_{P2}} \tag{6}$$

Where, V is ship velocity, P_{Prop} is the required propulsion power to develop velocity V, c_{P1} is a coefficient used for propulsion power and ship velocity matching, c_{P2} is a constant depending on hull form (c_{P2}=3 for conventional hull forms).

If during time interval ΔT_j ship speed is V'_j while the scheduled speed before optimization is V_j then the deviation of the propulsion power is:

$$\Delta P_{\mathrm{Pr}op,j} = c_{P1} \cdot \left(V'^{\,c_{P2}}_j - V_j^{c_{P2}} \right) \tag{7}$$

3. OPTIMAL ACTIVE POWER MANAGEMENT PROBLEM

3.1 Formulation

Minimize:

$$\mathrm{To}C = \sum_{j=1}^{T} \sum_{i=1}^{N_g} \left(St_{ij} \cdot \left(Fuel\_Cost_i \cdot SFC_i(P_{ij}) + OC_i \right) \cdot P_{ij} \cdot \Delta T_j + SC_{ij} \right) \tag{8}$$

Subject to:

→ Power balance constraint,

$$\sum_{i=1}^{N_g} P_{ij} = L_j + \Delta P_{\mathrm{Pr}opj}, \qquad \forall\ j \tag{9}$$

→ Minimum and maximum generator loading constraints,

$$P_{i,\min} < P_{ij} < P_{i,\max}, \qquad \forall\ i, j \tag{10}$$

→ Generator ramp rate constraint,

$$\frac{\left| P_{ij} - P_{i,j-1} \right|}{\Delta T_j} \le Rc_{i,\max}, \qquad \forall\ i, j \tag{11}$$

→ Minimum operation time of generator,

$$t_{\to \mathrm{OFF,i}} - t_{\to \mathrm{ON,i}} \ge \mathrm{T}_{\mathrm{ON\_min,i}}, \qquad \forall\ i \tag{12}$$

→ Minimum out of operation time of a generator,

$$t_{\to \mathrm{ON,i}} - t_{\to \mathrm{OFF,i}} \ge \mathrm{T}_{\mathrm{OFF\_min,i}}, \qquad \forall\ i \tag{13}$$

→ Blackout prevention constraint,

$$\sum_{i} St_{ij} \cdot P_{i,\max} - \bar{L}_j - \Delta P_{\mathrm{Pr}opj} \ge \max\left\{ P_{i,\max} \right\}, \qquad \forall\ j \tag{14}$$

→ GHG emissions constraint,

$$\frac{\sum_{i=1}^{N_g} c_i \cdot St_{ij} \cdot P_{ij} \cdot SFC_i(P_{ij})}{LF \cdot V_j} \le \mathrm{EEOI}_{\max} \tag{15}$$

→ Minimum - maximum ship speed constraint,

$$V_{\min} < V_j < V_{\max}, \qquad \forall\ j \tag{16}$$

→ Initial condition for the deviation of the actual travel distance from the scheduled,

$$\Delta S_0 = 0 \tag{17}$$

→ Final condition for the deviation of the actual travel distance from the scheduled one,

$$\Delta S_{\mathrm{T}} = 0 \tag{18}$$

→ Deviation of the actual traveled distance from the scheduled one at the intermediate ports,

$$\Delta S_j = 0 \qquad \forall\ j \in A \tag{19}$$

→ Minimum and maximum deviation of the actual traveled distance from the scheduled,

$$\Delta S_{\min,j} \le \Delta S_j \le \Delta S_{\max,j}, \qquad \forall\ j \tag{20}$$

Where, i denotes *i-th* generator, j denotes *j-th* time interval, A denotes the set containing time intervals corresponding to ship calls at intermediate ports and St_{ij} is a parameter being equal to 1 or 0 if the *i-th generator* is ON or OFF, respectively.

3.2 Solution method

Dynamic programming is used to solve the above constraint nonlinear optimization problem. Grid stages correspond to the time intervals of the examined time period while grid states contain generator-state vector. State vector used for the examined problem is defined in (21).

$$State = [\underbrace{D_{G_1} \ D_{G_2} \ \ldots \ D_{G_{N_g}}}_{Generators\ State} \ \underbrace{D_{\Delta S_1} \ D_{\Delta S_2} \ \ldots \ D_{\Delta S_{N_s}}}_{\Delta S_{bin}}] \tag{21}$$

Where, D_{Gi} is binary digit used to define *i*-th generator state of operation while the deviation from the initially scheduled travelled distance is quantified with a string, $\Delta S_{bin,\ell}$, of binary digits , $D_{\Delta S}$, with total number of digits, N_s.

The deviation from the scheduled speed can be easily calculated by using the deviation from travelled distance that is contained into the grid-state. Power production cost, *PC*, is minimized at each grid point by applying classical economic power dispatch based on the well-known Lagrange method. Afterwards, total cost of state ℓ at time interval t, $ToC_{t,l}$, is minimized according to (22).

$$ToC_{t,\ell} = \min\left\{PC_{t,\ell} + SC_{(t-1,k),(t,\ell)} + ToC_{t-1,k}\right\}, \forall k \;\; state\ at\ t-1 stage \tag{22}$$

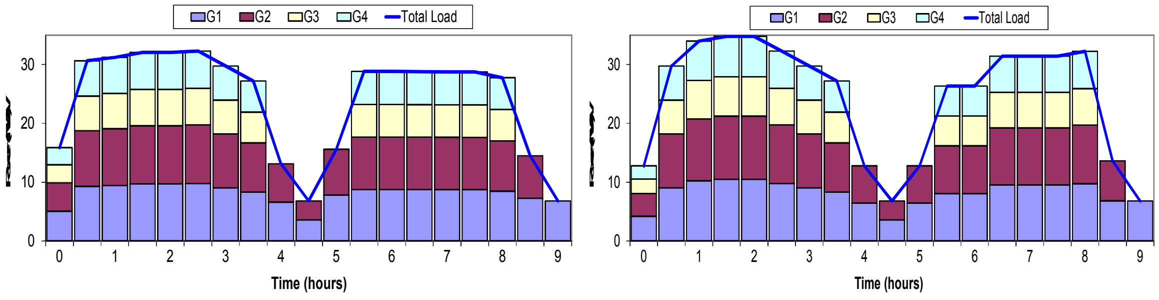
4. CASE STUDY

The proposed method is applied to the electric power system of a cruise-ferry with full electric propulsion and dc distribution grid. All the necessary technical parameters of the ship and the onboard power system are presented in Table 1. The examined cruise-ferry comprises 2 large electric propulsion motors supplied by the set of 4 electrical generators driven by different diesel engines. Two operation scenarios are examined next. In scenario 1, the proposed optimal power management method is applied while in the second scenario propulsion load is not adjusted and EEOI is not limited.

Table 1. Ship Power System Model Data

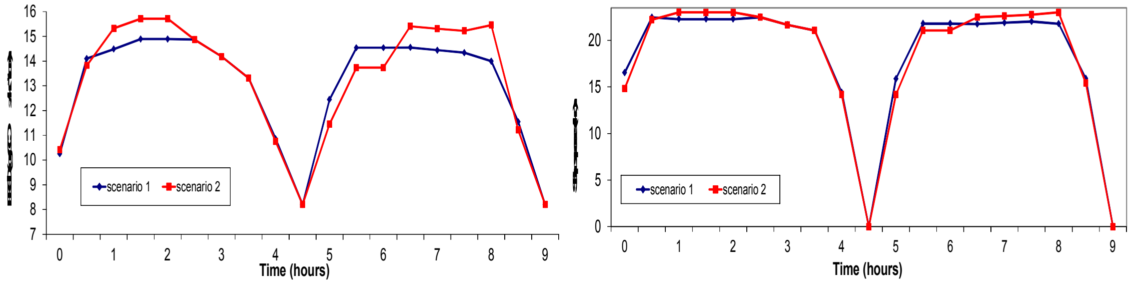
Ship Electric System Parameters				
	Gen 1	**Gen 2**	**Gen 3**	**Gen 4**
Nominal Power (MW)	10	10	15	15
Technical minimum (MW)	2	2	3	3
Minimum hours for generator being in operation or out of operation (h)	2/2	2/2	2/2	2/2
Generator Startup/Stop Cost (m.u.)	200/0	200/0	200/0	200/0
SFC (monetary unit/MWh)	$98.1+148.7\times P\ldots$ $+3.39\times P^2$	$86.5+145.8\times P\ldots$ $+3.69\times P^2$	$156.1+146.2\times P..$ $+2.28\times P^2$	$137.7+143.2\times P..$ $+2.485\times P^2$

Ship Parameters					
Type	Cruise ferry	Max. no. of vehicles (n_v)	700	EEOI$_{max}$($gCO_2/tn.kn$)	15
Nominal speed (kn)	24	Max. number of passengers	2500	Gross registered tons	60.000



a) b)

Figure 2. Generators power production. a) scenario 1, b) scenario 2.



a) b)

Figure 3. a) EEOI time evolution, b) Ship speed time evolution

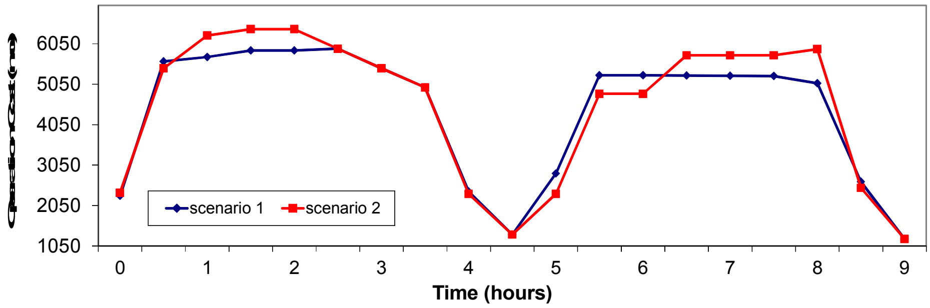


Figure 4. Operation cost time evolution

The powers produced by the electric generators are shown in stack form in Fig. 2. In scenario 1, propulsion power is adjusted and smaller deviations of total electric load occur. Generators 1 and 2 are less expensive than generators 3 and 4; thus they are operated continuously while 3 and 4 are used during high load periods. EEOI is successfully limited in scenario 1 as it is shown in Fig. 3.a while in scenario 2 it exceeds its upper limit. In scenario 1, ship speed is decreased when ship is in open sea, while it is increased, when ship is approaching or leaving from a port. In case of scenario 1 the total operation cost is 83.564m.u. that is 3% lower than that of scenario 2 (85.780m.u.).

5. CONCLUSIONS

In this paper an optimal power management method for AES is proposed aiming at operation cost minimization, GHG emissions limitation and, satisfaction of all ship power system technical and operational constraints concerning power balance, blackout avoidance, travel schedule etc. Despite the complexity of the problem the proposed method is proved efficient in minimizing the operation cost and limiting GHG emissions. Results obtained by applying the method to a cruise-ferry showed that operation cost can be reduced by almost 3% if propulsion adjustment together with EEOI limitation are applied with respect to operation without propulsion adjustment and GHG limitation.

ACKNOWLEDGEMENT

The work presented in this paper has been financially supported within the framework of the “DC-Ship” project (ARISTEIA-EXCELLENCE-I contract No 987/2012 of the General Secretariat Research and Technology of the Hellenic Government) co-financed by the European Union (European Social Fund – ESF) and Greek National funds through the Operational Program “Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) – Research Funding Program “ARISTEIA” (EXCELLENCE).

REFERENCES

1. Kanellos F.D., Tsekouras G.J., Prousalidis J., Onboard DC grid employing smart grid technology: Challenges, state of the art and future prospects, *IET Electrical Systems in Transportation*, 5 (1), pp. 1-11, 2015.
2. F.D. Kanellos, Optimal power management with GHG emissions limitation in All Electric Ship power systems comprising energy storage systems, *IEEE Trans. on Power Systems*, vol. 29, issue 1, pp. 330 -339, January 2014.
3. F. D. Kanellos, J. Tsekouras, J. Prousalidis, Control system for fuel consumption minimization–gas emission limitation of full electric propulsion ship power systems, *Proc. of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 0(0), 1–12, 2012.
4. Man Diesel & Turbo (2012, Aug.). Basic Principles of Ship Propulsion. [Online]. Available: http://www.mandieselturbo.com/0000245/Press/Publications/Technical-Papers.html?page=3.