International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0713

FUEL EFFICIENCY IMPROVEMENT FOR A CRUSIE SHIP BY OPTIMIZATION OF POWER GENERATON SCHEDULING

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ABSTRACT

Centralized power generation of the integrated electric propulsion enables various optimization techniques to automatically activate diesel generators to respond the load changes in an optimal manner. In this study, the power generation scheduling problem is formulated with constraints for a large cruise ship. The problem is solved with assistance of SFC modelling by three recent meta-heuristic optimization methods, namely grey wolf optimizer, ant lion optimizer and whale optimization algorithm. Simulation results demonstrate the proposed methods ensure minimum fuel consumption compared with baseline data for certain load profiles.

Keywords: integrated electric propulsion, power generation scheduling, optimization methods, fuel efficiency

NOMENCLATURE

Abbreviations	
ALO	Ant lion optimizer
GA	Genetic algorithm
GWO	Grey wolf optimizer
PSO	Particle swarm optimization
MCR	Maximum continuous rating
SFC	Specific fuel consumption
WOA	Whale optimization algorithm

1. INTRODUCTION

Extensive electrification of ship power systems appears a promising solution to comply with the incremental tightening of environmental restrictions by means of operating with higher fuel efficiency. An energy-saving feature of the integrated platform is to supply all electrical loads through a set of power generation units. This centralized power concept enables various optimization techniques to distribute an appropriate amount of load for individual diesel generators. Conceptually, an optimization algorithm should be able to select an optimal number of active generators to respond the load changes, while non-selected generators should be kept inactive. According to a survey of literature, optimization techniques involved with power generation scheduling include dynamic programming [1], genetic algorithm (GA) [2] and particle swarm optimization (PSO) [3]. In this study, three recent optimization methods: grey wolf optimizer (GWO), ant lion optimizer (ALO) and whale optimization algorithm (WOA) are implemented to minimize fuel consumption of a luxury large cruise vessel. More specifically, the fuel saving performance of the proposed methods are measured by comparing with a baseline and well-known optimization techniques, namely GA and PSO.

2. MODELING OF SPECIFIC FUEL CONSUMPTION

The fuel consumption at various engine loading condition can be derived from the engine manufacturer. The selected marine engine is Wartsila 46F V-type installed as prime movers on the Britannia, an integrated electric propulsion cruise vessel operating in European and Caribbean Seas. Table 1 shows the power system configuration of the Britannia.

Cubic spline interpolation is used to model the SFC data as it is able to accurately model the curve with minimum norm of residues. The mathematical equations for determining the SFC value at any given loads are as follows:

$$S(p_j)=\begin{cases}-0.5542(p_j)^3-45.965(p_j)+211.2, & p_j\in[0,0.25]\\ 156.37(p_j)^3-117.69(p_j)^2-16.542(p_j)+208.75, & p_j\in(0.25,0.50]\\ -701.52(p_j)^3+1169(p_j)^2-659.83(p_j)+315.95, & p_j\in(0.50,0.75]\\ 4104.2(p_j)^3-9643.9(p_j)^2+7749.9(p_j)-1711.5, & p_j\in(0.75,0.85]\\ -1826.4(p_j)^3+5479.2(p_j)^2-5404.8(p_j)+1930.7, & p_j\in(0.85,1]\end{cases} \tag{1}$$

where p_j is the power assigned to jth engine and $SFC(p_j)$ is the specific fuel consumption.

The SFC curve for the Wartsila 46F V-type engines is shown in Fig. 1. The figure also shows a comparison between cubic spline and polynomial interpolation methods. The low-degree polynomials suffer from higher percentage of error, while the high-degree polynomials suffer from the Runge's phenomenon which refers to a problem of oscillation at the edge of intervals.

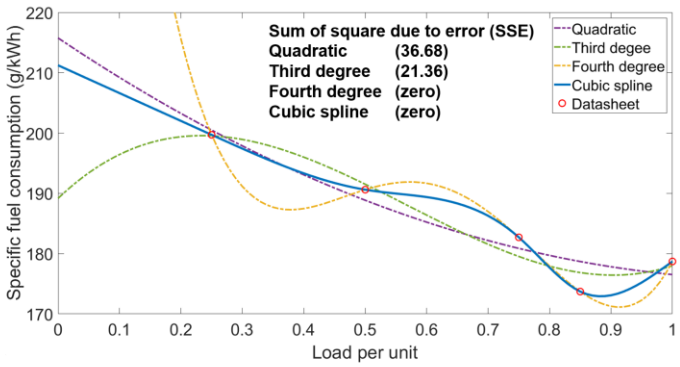

Fig. 1 A comparison of interpolation methods.

Table 1 Parameters of the Britannia

Power system configuration				
Propulsion	2 x Propulsion motor VEM Sachsenwerk GMBH Total propulsion power 2 x 18,000 kW			
Power generation	2 x Wartsila 12V46F and 2 x Wartsila 14V46F Total installed power 62,400 kW Alternator efficiency 0.976			
Prime mover	Gen 1	Gen 2	Gen 3	Gen 4
Model	14V46F	14V46F	12V46F	12V46F
Power (kW)	16,800	16,800	14,400	14,400

3. OPTIMIZATION PROBLEM FORMULATION

The primary objective of power generation scheduling is to minimize total fuel consumption governed by the SFC curve. The optimal operating condition of the selected engine is defined between 80 - 90% of maximum continuous rating (MCR), whereas the lightly loaded engine consumes significantly higher fuel. The power management should be able to automatically switch on and off each individual generator to coincide with instantaneous load changes and to keep the average engine load closest possible to optimal operating area. The load allocation problem can be formulated as follows:

By considering N number of generators and by assuming the rated power of Nth generator is maximum, the rating of individual prime movers to the base of maximum rating is given in per unit (pu) by:

$$\vec{P}_{pu}^{max} = \frac{\vec{P}^{max}}{P_N^{max}} \tag{2}$$

The power assigned to jth generator running at time interval Δt_i is given by $p_{j,i}$ and its specific fuel consumption is defined by $SFC(p_{j,i})$. The amount of fuel consumed by all diesel generator for time horizon $T_{horizon}$ is given by:

$$F(\vec{p}) = \sum_{i=1}^{T_{horizon}} \sum_{j=1}^{N} \left[SFC(p_{j,i}) \cdot p_{j,i} \cdot \vec{P}_N^{max} \right] \tag{3}$$

The optimization problem then can be formulated as:

$$Minimize \sum_{i=1}^{T_{horizon}} \sum_{j=1}^{N} \left[SFC(p_{j,i}) \cdot p_{j,i} \cdot \vec{P}_N^{max} \right] \tag{4}$$

The constraints of the optimization problem are defined as follows:

1) Power balance constraint:

$$P_{L,i} = \sum_{j=1}^{N} p_{j,i} \cdot \vec{P}_N^{max} \tag{5}$$

where $P_{L,i}$ is the total power demand at Δt_i.

2) Minimum and maximum generator loading constraint:

$$p_j^{min} \le p_{j,i} \le p_j^{max} \tag{6}$$

where $p_j^{min} = 0$ and $p_j^{max} = \vec{P}_{pu}^{max}$.

3) Start-up load increase rate constraint:

$$\frac{P_{j,i} - P_{j,i-1}}{\Delta t_i} \le R_{start-up,j} \tag{7}$$

where $R_{start-up,j}$ is maximum allowed load increase rate for a start-up generator.

4) Instant load step constraint:

$$\left| P_{j,i} - P_{j,i-1} \right| \le R_{up/down,j} \tag{8}$$

where $R_{up/down,j}$ is maximum permissible load ramp-up or ramp-down.

4. IMPLEMENTATION OF OPTIMIZTION METHODS

Three recent meta-heuristic optimization methods: GWO, ALO and WOA are proposed to solve the formulated optimization problem. The three methods were originally developed by Seyedali Mirjalili in 2014, 2015 and 2016 respectively and have been increasingly used in a wide range of engineering applications, especially research in power systems. In this section, brief details of WOA are only given and its complete details can be referred to [4] including the details of GWO [5] and ALO [6].

The WOA is inspired by a special hunting method of humpback whales called bubble-net hunting strategy. Conceptually, humpback whales dive down to an appropriate water depth and start to create bubbles in a spiral shape to surround prey keeping them from escaping. All whales then simultaneously swim up toward the surface to feed on the trapped prey. The spiral bubble-net hunting maneuver is mathematically modeled and its pseudo-code including relevant equations are presented in Algorithm I.

Algorithm I Whale optimization algorithm (WOA)

Parameters: t = current iteration, b = a constant for defining the shape of the logarithmic spiral, $\vec{a}$ = a linear decrease from 2 to 0, $\vec{r}$ = a random vector in [0, 1], l = a random number in [-1, 1], p = a random number in [0, 1], $\vec{X}$ = position vector, X^* = position vector of the best solution and $\vec{D}' = \left|\vec{X}^*(t) - \vec{X}(t)\right|$

$\vec{A}$ and $\vec{C}$ = coefficient vectors and can be calculated by:

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \tag{9}$$

$$\vec{C} = 2 \cdot \vec{r} \tag{10}$$

Initialize the whale population X_i (I = 1, 2, ..., n)

Calculate the fitness of each search agent (X^*)

while (t < maximum number of iterations)

for each search agent: Update *a, A, C, l* and *p*

if 1 (p < 0.5)

if 2 ($|A|$ < 1): Update the position of the search agent by:

$$\vec{D} = \left|\vec{C} \cdot \vec{X}^*(t) - \vec{X}(t)\right| \tag{11}$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{D} \tag{12}$$

else if 2 ($|A| \geq 1$): Select a random search agent (X_{rand})

Update the position of the search agent by:

$$\vec{D} = \left|\vec{C} \cdot \vec{X}_{rand} - \vec{X}\right| \tag{13}$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A} \cdot \vec{D} \tag{14}$$

end if 2

else if 1 (p ≥ 0.5): Update the position of the search agent by:

$$\vec{X}(t+1) = \vec{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^*(t) \tag{15}$$

end if 1

end for: Update X^* if a better solution is found

t = t+1

end while: Return X^*

5. RESULTS AND DISCUSSION

The case study is based on actual voyages of the Britannia operating in the Norwegian Sea. The voyage data or baseline data is obtained from the Norwegian coastal authority and has been validated by [7]. The selected voyages comprise of three load profiles: low, medium and high-speed load profiles. The classification of the profile is determined by the majority of speed used for a voyage, i.e. the majority of speed between 13 – 15 knots, 16 – 18 knots and 19 – 21 knots are for low, medium and high-speed load profile, respectively. Fig. 2 shows data on speed, load per unit and fuel consumption for the profiles.

By applying conventional equal loading of generators and by considering alternator efficiency of 0.976, the fuel consumption obtained is nearly identical with the baseline data as shown in Fig. 3. Thus, it may assume the selected profiles are not optimized. The proposed optimization techniques are then applied to reschedule operating state of individual generators. The well-known evolutionary algorithms, GA and PSO, are also applied for the purpose of making a comparison. The optimization performance is determined by the fitness value which is the sum of SFC of individual active diesel generators. Controlled parameters include maximum iteration of 200 and population size defined by 10 times the number of dimensions.

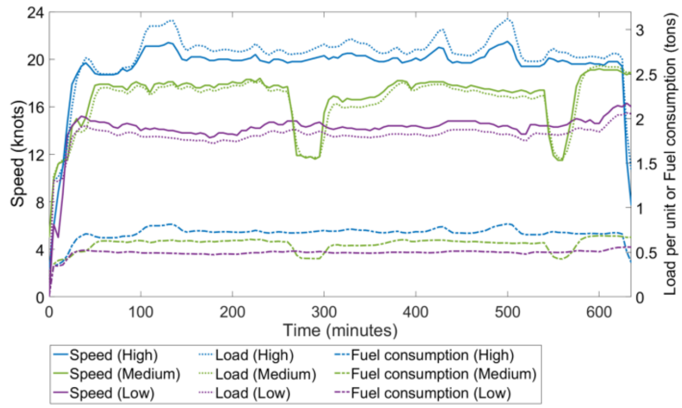

Fig. 2 Data for low, medium and high-speed profiles.

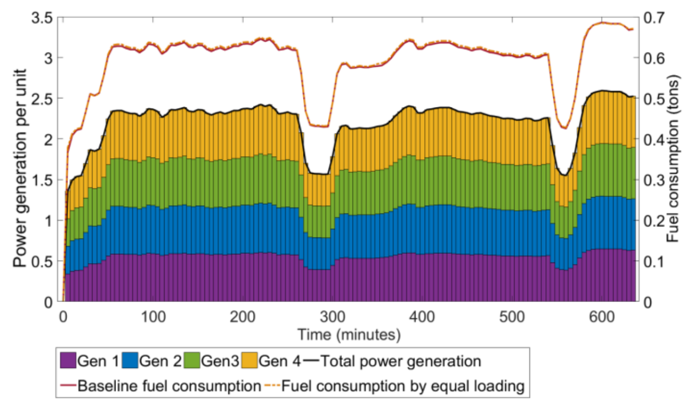

Fig. 3 Equal loading of generators and its fuel consumption compared with the baseline.

Fig. 4 shows the convergence rate of all algorithms for a load demand of 2.5 pu (1 pu equals 16,800 kW). GWO, ALO and WOA are able to find an optimal solution of 519.11, while GA and PSO are often stuck in local optima at 524.46.

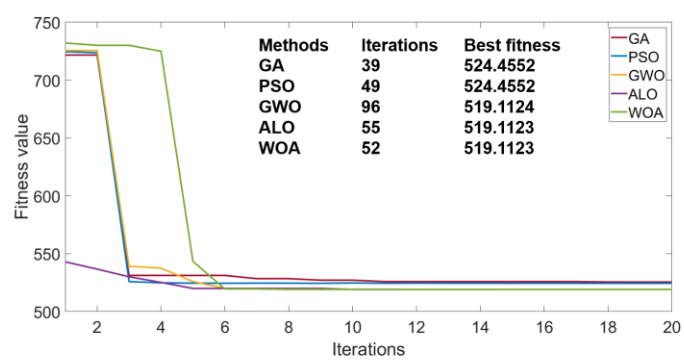

Fig. 4 A comparison of convergence rate at 2.5 pu load

The load dependent operating states of individual generators are optimally scheduled by using ALO and WOA as respectively shown in Fig. 5 and Fig. 6. For the medium-speed load profile, generator 3 and 4, and generator 2 in higher load condition, mostly operate in their optimal SFC points, while generator 1 in some periods operates within lightly loaded condition to fulfil the load demands. For high-speed load profile, all generators are started up when the load demand approaching 3 pu. Generator 2, 3 and 4 operate with low SFC condition for vast majority of time, while generator 1 reaches its optimal SFC area when surpassing 3 pu load. By comparing with the baseline, the fuel saving performance of the two profiles can be estimated by 6.85% and 4.32%. Table 2 summarizes the average fuel saving results of all algorithms applied for three different load profiles. The three recent optimizations methods provide greater performance in minimizing fuel consumption compared with GA and PSO. The maximum fuel saving potential is estimated by 7.74%, 6.88% and 4.31% for low, medium and high-speed profiles, respectively. By comparing within the three proposed methods, they are competitive to one another, though the WOA technique appears to save more fuel in the low-speed load profiles. The limited capability to minimize fuel consumed in the course of higher loads is due to limited searching space for search agents. At low load condition, the smaller number of active generators are sufficient to satisfy the demand. Thus, fuel efficiency could be improved by optimally allocating the load and also by minimizing the number of generators. Meanwhile, all generators need to be switched on and operated in the same manner with the equal loading scheme when the load demand approaching the maximum limit of power generation capability.

Table 2 Average fuel saving of all algorithms

Load profiles	Algorithms				
	GA	PSO	GWO	ALO	WOA
Low speed	5.60%	7.05%	7.24%	7.25%	7.74%
Medium speed	6.04%	6.78%	6.87%	6.88%	6.88%
High speed	4.21%	4.22%	4.22%	4.22%	4.31%

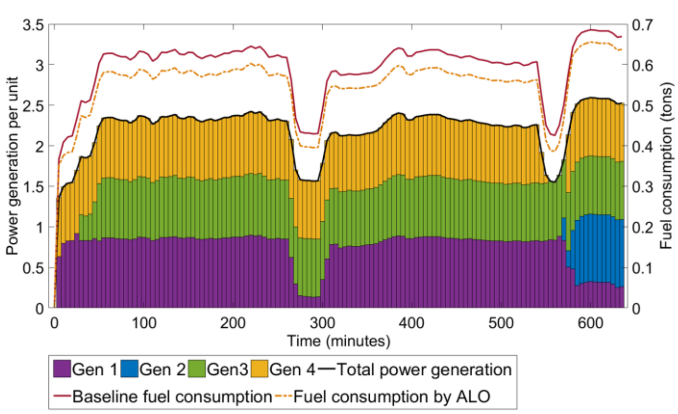

Fig. 5 Optimal scheduling by ALO for medium-speed profile.

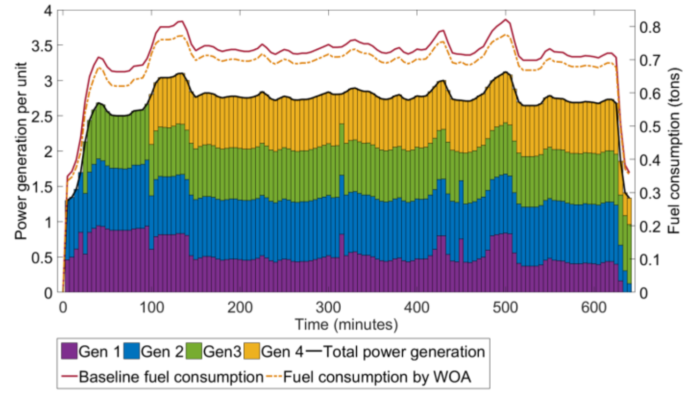

Fig. 6 Optimal scheduling by WOA for high-speed profile.

6. CONCLUSIONS

The optimal load allocation for diesel generators onboard the cruise ship by using three recent optimization methods: GWO, ALO and WOA are able to reduce fuel consumption in the range of 4.22 - 7.74% for certain load profiles. The new methods also demonstrate better performance than GA and PSO in terms of best fitness obtained. The optimal power generation scheduling by using an appropriate optimization technique hence proves to be an effective method to make onboard energy systems more efficient. For future research, the fuel efficiency could be further improved by forthcoming optimization techniques and by modification of the ship power systems such as the use of dual fuel engines or energy storage.

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