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Fuel Efficiency Improvement by Optimal Scheduling of Diesel Generators using PSO in Offshore Support Vessel with DC Power System Architecture

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***Abstract*—This paper presents optimal generation scheduling for minimization of fuel consumption (FC) in a typical offshore support vessel with DC power system architecture employing four identical diesel generator (DG) sets. FC is analyzed for (i) equal load sharing among DGs in AC architecture, (ii) equal load sharing among DGs in DC architecture and (iii) optimal load sharing among DGs in DC architecture using Particle Swarm Optimization (PSO). Due to the presence of non-linearity in Specific FC (SFC) curves of the diesel engines, the PSO algorithm is used. The SFC-vs-load relationship obtained from Brake SFC (BSFC) map of the diesel engines is characterized using a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) interpolation. A solution to problem has been attained by comparing yearly fuel consumption in the three cases for the load profile of target vessel. This method can be applied to any vessel equipped with multiple generation units having DC power system architecture.**

Keywords*—AC power system architecture, DC power system architecture, diesel electric propulsion, generation scheduling, particle swarm optimization, specific fuel consumption.

I. INTRODUCTION

Ever decreasing fossil fuel resources and degrading climate have led to more stringent regulations for fuel economy and gas emissions in marine vessels [1]. This attracted attention of the researchers towards the issues related to minimization of fuel consumption and emissions [2]. Of late, various methods have been developed for reduction of fuel consumption in ships [3]. Hybrid systems combining mechanical and electric propulsion systems or shaft generators have been proposed for efficient operation under different operating modes of vessel. Due to various benefits, the electric propulsion system is preferred for the vessels with varying velocity and dynamic positioning (DP) operation, such as the supply vessels, floating production vessels, drill ships, ice breakers and naval ships [4].

In conventional vessels having AC power architecture, the diesel engines coupled to the synchronous generators are operated at synchronous speed, which is decided by the generator poles and bus frequency. According to the brake specific fuel consumption (BSFC) maps of the diesel engines, such fixed speed operation of the diesel engine is fuel efficient only within a limited range of loading [4]. Most of the diesel engines operate at lower SFC and efficiently within a loading range of 70-100% of nominal loading. However, for the vessels operating in DP mode, the average electric thruster loads are normally low [4]. At lower loading, the SFC rises abruptly and causes higher fuel consumption [5]. One of the effective solutions for this problem is the deployment of DC power architecture in vessel, where each DG set is connected to a DC bus-bar through a power electronic converter [6]. Unlike fixed speed operation of all the DG sets in the AC architecture, each DG set operates independently at variable speed in the DC architecture. Hence lower SFC can be achieved even for a lightly loaded engine by operating it at an optimal speed.

Optimal load sharing among the DGs in a vessel with AC architecture has been investigated by many researchers. A generalized BSFC map with a second or higher order polynomial and exponential functions based curve fitting have been used to characterize the relationship between SFC and loading [4], [8]. However, the SFC data for limited operating points leads to inconsistent SFC characterization. Investigations on optimal scheduling of variable speed DGs in ship electric propulsion system is not available in literature. Such optimal generation scheduling for minimization of fuel consumption in an offshore support vessel (OSV) is presented in this paper. Accuracy of the SFC data is ensured by employing detailed BSFC map of the diesel engine [7]. For optimization, two classical methods are available, viz. direct search method and gradient search method [9]. The former uses only objective function and constraints, and is slow due to many function iterations. The latter uses first and/or second order derivatives and is faster, but inefficient with discontinuous and non-differentiable objective functions. Such limitations can be avoided by using evolutionary algorithms [10]. One of the most prominent evolutionary algorithms is Particle Swarm Optimization (PSO) [11], which is based on the principles of movement of organisms in a bird flock or a fish school. The PSO is applied for optimal scheduling of DGs in the present study for its efficacy in finding a global optimal solution quickly even when the solution search space is too large [11].

A typical DP operated OSV equipped with four identical DGs of 9400 kW total capacity is analysed for the following three cases: Case-I- equal load sharing among DGs in AC power architecture; Case-II- equal load sharing among DGs in DC power architecture; and Case-III- PSO based optimal load sharing among DGs in DC power architecture. The next section describes the two power architectures and load profile of the target OSV. Section III presents SFC modelling of the employed diesel engine. Section IV and V describe the optimization problem formulation and PSO respectively. In Section VI, the results for the case studies are discussed and Section VII presents the conclusions.

II. OFFSHORE SUPPORT VESSEL

A single line diagram representation of diesel-electric propulsion system with key components including DG sets with synchronous machines and variable speed thruster drives with induction motors in the typical AC and DC power system distribution networks are shown in Fig. 1 and Fig. 2 respectively.

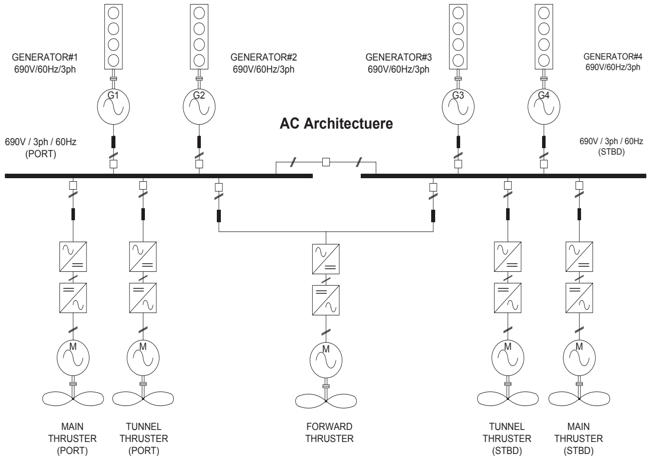

Fig. 1: Offshore Support Vessel with AC architecture

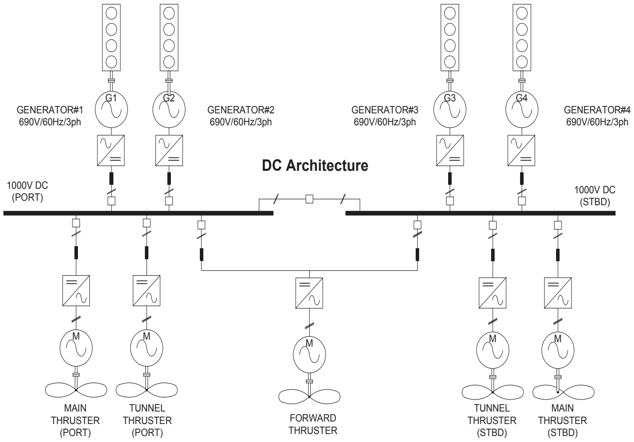

Fig. 2: Offshore Support Vessel with DC architecture

For the aforesaid cases I, II and III, four identical DGs, each of 2350 kW capacity are used. The main bus-bars are supplied at 690 V, 60 Hz in AC architecture and 1000 V in DC architecture. The bus-bars are divided into port side and starboard side sections. Depending on the operating philosophy of the ship operator, the two buses may operate separately or connected through a bus-tie. Fig. 3 shows load profile of the typical OSV under study. The percentage of operation time is plotted for different loading under various operating modes. The load profile of the OSV has decisive influence in the power system design process. It can be observed that the vessel operates in DP and transit modes for 55.42% and 22.50% of total time respectively. The high DP and transit towing modes require more power while the low DP and transit supply modes require less power. Based on this profile, the yearly fuel consumption for the three cases is compared in Section VI.

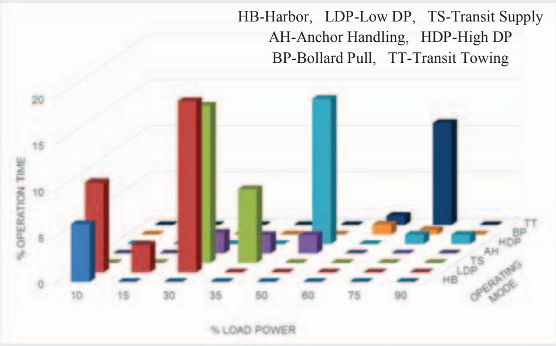

Fig. 3: Load profile of Offshore Support Vessel

III. MODELLING OF SPECIFIC FUEL CONSUMPTION

The accuracy of modelling the SFC plays a vital role in the end results of the optimal DG scheduling for minimum FC. The SFC values for the 2350 kW diesel engine are obtained from the BSFC map [7] at discrete values of load in the entire load range of the engine. The SFC values corresponding to fixed speed operation in the AC architecture and variable speed operation in the DC architecture are listed in Table-I.

TABLE I: SFC of 2350 kW Diesel Engine

AC Architecture		**DC Architecture**	
Load (kW)	**SFC (g/kWh)**	**Load (kW)**	**SFC (g/kWh)**
680	280	270	250
860	235	300	230
1120	215	460	210
1330	209	580	203
1490	207	700	199
1620	205	830	197
1990	203	1420	197
2010	203	1530	199
2350	205	1540	203
		2350	203

Based on the above SFC data, the SFC-vs-power relationship of the engine is characterized in form of 3^{rd} and 5^{th} order polynomials ((1) and (2) for AC architecture; and (3) and (4) for DC architecture) and Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) interpolation using the MATLAB curve fitting toolbox, as follows.

$$\begin{aligned} FC(P_i) &= -5.05e-008(P_i^3) + 0.0002723(P_i^2) \\ &\quad - 0.4825(P_i) + 485.3 \end{aligned} \tag{1}$$

$$\begin{aligned} FC(P_i) &= -7.87e-14(P_i^5) + 6.694e-10(P_i^4) \\ &\quad - 2.239e-6(P_i^3) + 0.003693(P_i^2) \\ &\quad - 3.026(P_i) + 1202 \end{aligned} \tag{2}$$

$$\begin{aligned} FC(P_i) &= -2.472e-008(P_i^3) + 0.0001131(P_i^2) \\ &\quad - 0.1565(P_i) + 263 \end{aligned} \tag{3}$$

$$\begin{aligned} FC(P_i) &= -1.79e-14(P_i^5) + 1.348e-10(P_i^4) \\ &\quad - 4.02e-6(P_i^3) + 0.0005944(P_i^2) \\ &\quad - 0.4285(P_i) + 316 \end{aligned} \tag{4}$$

The three characteristics are plotted in Fig. 4(a) and (b) for the AC and DC architectures and a comparison of their accuracy is given in Table II in terms of the Sum of Squared Errors (SSE). The SFC characterization based on PCHIP interpolation method is adopted in the present study to achieve highest accuracy. Subsequently, piecewise 2^{nd} order polynomials as given in (5)-(21) are used to characterize the SFC-power relationship for the two architectures.

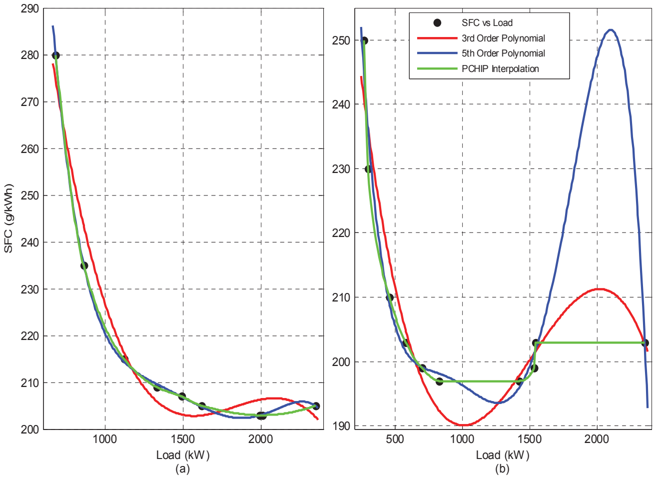

Fig. 4: Curve fittings of SFC-power relationships for (a) AC architecture and (b) DC architecture

TABLE II: SFC of 2350 kW Diesel Engine

Characterization Method	**Sum of Squared Error (SSE)**	
	AC	**DC**
PCHIP Polynomial	0	0
3^{rd} Degree Polynomial	159.7	190.8
5^{th} Degree Polynomial	0.9742	75.93

Piecewise Polynomials for AC Architecture

For $680 \leqslant P_i < 860$

$$SFC(P_i) = 0.0005849(P_i^2) - 1.149(P_i) + 79 \tag{5}$$

For $860 \leqslant P_i < 1120$

$$SFC(P_i) = 0.0005849(P_i^2) - 1.149(P_i) + 79 \tag{6}$$

For $1120 \leqslant P_i < 1330$

$$SFC(P_i) = 4.3e - 5(P_i^2) - 0.1343(P_i) + 312 \tag{7}$$

For $1330 \leqslant P_i < 1490$

$$SFC(P_i) = 1.546e - 5(P_i^2) - 0.05551(P_i) + 255 \tag{8}$$

For $1490 \leqslant P_i < 1620$

$$SFC(P_i) = -5.38e - 6(P_i^2) - 0.00102(P_i) + 217 \tag{9}$$

For $1620 \leqslant P_i < 1990$

$$SFC(P_i) = 1.934e - 5(P_i^2) - 0.0749(P_i) + 276 \tag{10}$$

For $1990 \leqslant P_i < 2010$

$$SFC(P_i) = 5.377e - 6(P_i^2) - 0.02151(P_i) + 225 \tag{11}$$

For $2010 \leqslant P_i \leqslant 2350$

$$SFC(P_i) = 2.217e - 5(P_i^2) - 0.091(P_i) + 297 \tag{12}$$

Piecewise Polynomials for DC Architecture

For $270 \leqslant P_i < 300$

$$SFC(P_i) = 0.005615(P_i^2) - 3.91(P_i) + 897 \tag{13}$$

For $300 \leqslant P_i < 460$

$$SFC(P_i) = 0.000558(P_i^2) - 0.5412(P_i) + 342 \tag{14}$$

For $460 \leqslant P_i < 580$

$$SFC(P_i) = 0.0001511(P_i^2) - 0.2151(P_i) + 277 \tag{15}$$

For $580 \leqslant P_i < 700$

$$SFC(P_i) = 8.7e - 5(P_i^2) - 0.145(P_i) + 258 \tag{16}$$

For $700 \leqslant P_i < 830$

$$SFC(P_i) = 7.711e - 5(P_i^2) - 0.1343(P_i) + 256 \tag{17}$$

For $830 \leqslant P_i < 1420$

$$SFC(P_i) = -9.339e - 20(P_i^2) + 197 \tag{18}$$

For $1420 \leqslant P_i < 1530$

$$SFC(P_i) = 0.0002055(P_i^2) - 0.589(P_i) + 619 \tag{19}$$

For $1530 \leqslant P_i < 1540$

$$SFC(P_i) = 0.4(P_i) - 413 \tag{20}$$

For $1540 \leqslant P_i \leqslant 2350$

$$SFC(P_i) = -4.6e - 19(P_i^2) + 1.83e - 15(P_i) + 203 \tag{21}$$

where, SFC(P_i) is SFC of i^{th} DG for load power P_i.

IV. OBJECTIVE FUNCTION FORMULATION

The optimization problem is to solve the generation scheduling in order to minimize the total fuel consumption. In the present study, P_{Load} denote total load demand, *SFC* and *FC* denote specific fuel consumption and fuel consumption of the i^{th} DG for the assigned load power P_i to that DG.

The total fuel consumption of the vessel per hour is the summation of fuel consumption of the individual diesel engines given as,

$$FC = \left[\sum_{i=1}^{N} SFC(P_i) * P_i \right] \tag{22}$$

where, N is the total number of DGs and FC is fuel consumption in kg/hr.

Hence, the objective function can be given as in (23) with the constraints as in (24) in general, and (25) and (26) for the AC and DC architectures respectively.

$$f = min\left(\sum_{i=1}^{N} FC_i\right) \tag{23}$$

$$\sum_{i=1}^{N} P_i = P_{Load} \tag{24}$$

$$680kW \leqslant P_i \leqslant 2350kW \tag{25}$$

$$270kW \leqslant P_i \leqslant 2350kW \tag{26}$$

The minimum loading limits of 680 kW and 270 kW for the 2350 kW diesel engine for AC and DC architectures respectively are in accordance with the BSFC map of the engine [7] with an assumption that the SFC is very high below these limits.

V. PARTICLE SWARM OPTIMIZATION

The PSO is a population-based optimization method, first proposed by Kennedy and Eberhart [11]. The PSO is originally inspired by the sociological behaviour associated with bird flocking and fish schooling. It is used to find a solution to an optimization problem in a search space and predict behaviour of all particles in the presence of various constraints and objectives. The procedure involved in PSO based approach for minimizing FC of the OSV by optimally scheduling the DGs in DC architecture is described below.

The PSO algorithm starts with generating a swarm of particles randomly to solve the objective problem in the feasible region of the search space. Each particle is characterized by its position s_i^k and velocity v_i^k and each particle recalls its best position "*pbest*" associated with the best fitness value (i.e., the total fuel consumption) and each particle records the best position achieved by the entire swarm "*gbest*". In each iteration, the velocity of each particle is modified using its current velocity and its distance from personal best position "*pbest*" and global best position "*gbest*" according to (27).

$$\begin{aligned} v_i^{k+1} &= wv_i^k + c1 * rand() * (pbest_i - s_i^k) \\ &\quad + c2 * rand() * (gbest_i - s_i^k) \end{aligned} \tag{27}$$

where,
w: Inertia weight
c_1, c_2: Acceleration coefficients
v_i^k: i^{th} dimension velocity component at k^{th} iteration
s_i^k: Current position in the i^{th} dimension at k^{th} iteration
rand(): Random number generator between 0 and 1
$pbest_i$: Personal best position value in the i^{th} dimension
$gbest_i$: Global best position value in the i^{th} dimension.

The inertia weight *w* specifies how much of the previous velocity is to be retained for the next iteration. In general, a linearly decreasing inertia weight is used from 0.9 to 0.4. As a result, the particles can explore a large area in the beginning of the simulation, when the inertia weight is large and to refine the search later by using a decreasing inertia weight.

The acceleration constants *c1* and *c2* can be understood as a balance between exploration (searching for good solution) and exploitation (using success of others) respectively. They also represent the balance between individuality and sociality. Ideally, individuals prefer being individualistic, yet they want to know what others have achieved.

After the velocity update, each particle explores the search space of the problem for a better solution, given as,

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{28}$$

The personal best position of each particle is updated after the k^{th} iteration as,

$$pbest = \begin{cases} s; & \textit{if f(s)}\leqslant\textit{f(pbest)} \\ pbest; & \textit{if f(s)}> \textit{f(pbest)} \end{cases} \tag{29}$$

where, f is the fitness function.

The global best position among the personal best position of particles is updated after the k^{th} iteration as,

$$gbest = \begin{cases} pbest; & \textit{if f(pbest)}\leqslant\textit{f(gbest)} \\ gbest; & \textit{if f(pbest)}> \textit{f(gbest).} \end{cases} \tag{30}$$

This process of updating the particle position-velocity, and particle best and swarm best values continues until the best solution is found. The PSO parameters used for the simulations are listed in Table III.

TABLE III: PSO Parameters

Parameter	**Value**
No of particles	100
Maximum inertia weight	0.9
Minimum inertia weight	0.4
c1 and c2	1.49
Number of generations	100

VI. RESULTS AND DISCUSSIONS

This section presents the results related to the DG scheduling for the following three cases: Case-I- equal load sharing among DGs in AC architecture; Case-II- equal load sharing among DGs with DC architecture; and Case-III- PSO based optimal load sharing among DGs in DC architecture. For all the three cases, four DGs, each of 2350 kW capacity are used. The minimum and maximum power generation limits for each DG are 680 kW and 2350 kW respectively in the AC architecture and 270 kW and 2350 kW respectively in the DC architecture. In all the cases, the load sharing of individual DGs is calculated for discrete values of total load from 680 kW to 9400 kW in steps of 5% of nominal load of 9400 kW.

In Case-I and Case-II, each operating DG shares equal load, while the minimum possible number of DGs are operated depending on the total load demand and the constraints given by (24-26). For Case-III, the optimum load sharing among the

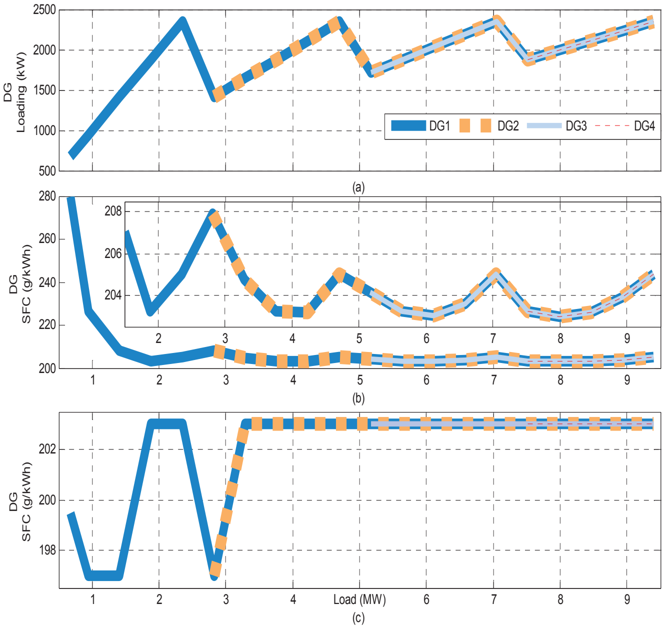

Fig. 5: (a) Loading of operating DGs for Case-I and Case-II; and SFC of operating DGs for (b) Case-I and (c) Case-II, against total load demand

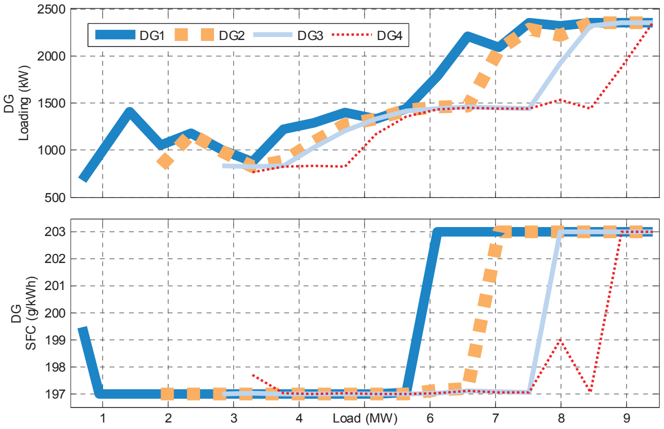

Fig. 6: Loading and SFC of operating DGs against load demand for Case-III

operating DGs is calculated using the PSO as described in the previous section for minimizing the total FC. Here, different combinations of operating DGs exist for certain loading, while satisfying the given constraints, e.g. total load demand 2820 kW can be supplied by loading only DG1 and DG2 optimally or by loading only DG1, DG2 and DG3 optimally. The SFC is minimum in the latter case. Essentially, this is a Unit Commitment (UC) problem. However, for the 4 identical DGs, the UC is not too complex and is performed manually in the present investigation. For all such loading points, the PSO has been applied for all the possibilities of UC to arrive at the minimum FC solution.

The variations in the loading of each operating DG and corresponding SFC values are plotted against total load demand in Fig. 5 for Case-I and II and in Fig. 6 for Case-III. The variations in the system SFC and system FC are plotted against total load demand in Fig. 7 for Case-I, II and III for the purpose of comparing the performance.

A. *Case-I- Equal load sharing among DGs in AC architecture*

The operating DGs are sharing equal load (see Fig. 5 (a)) and have the same SFC for a given load demand (see Fig. 5 (b)). As the total load demand increases, the load sharing of individual DGs increases with corresponding fall in the SFC. The SFC is minimum at the load demand, which is equal to an integer multiple of 2000 kW, e.g. 2000 kW, 4000 kW, etc., which corresponds to minimum SFC point on the SFC-load curve of the DG (see Fig. 4). However, for the load demands just above these points, all the DGs operate at higher SFC.

B. *Case-II- Equal load sharing among DGs in DC architecture*

The operating DGs are sharing equal load same as Case-I (see Fig. 5 (a)) and have the same SFC for a given load demand (see Fig. 5 (c)). It can observed from Fig. 5 (c) that the SFC values are quite lower in Case-II as compared to Case-I for the same loading conditions. This is because the SFC values are lower corresponding to variable speed operation (see Table I). The SFC is constant after certain total load demand i.e.3760 kW, as the load sharing among individual DGs is above 1540 kW, which corresponds to constant SFC value of 203 g/kWh (see Table I).

C. *Case-III- PSO based Optimal load sharing among DGs in DC architecture*

The operating DGs are sharing the load unequally, which is calculated using the PSO so as to minimize the system SFC and FC for a given load demand (see Fig. 6). It can be observed that the PSO allocates the loading such that all the operating 2350 kW DGs operate at a load corresponding to the minimum possible SFC point. This results in significant reduction in the system FC as compared to Case-I and Case-II throughout the total load demand range (see Fig. 7). Importantly, the reduction in system SFC and FC is prominent for the load demands just above the integer multiple of individual DG capacity where PSO is scheduling the DGs optimally, e.g. for 2820 kW of loading, instead of allocating 2 DGs, the PSO schedules 3 DGs, which consumes less fuel. In addition, it can be observed from Table III that the PSO based optimal scheduling of DGs improves the performance of the system by increasing the availability of the DGs in the load range 2820 kW to 7050 KW. That is, the operating DGs can share the load without any delay when there is a sudden change in the load demand in this region.

D. *Performance comparison for OSV load profile*

For the load profile of OSV in Fig. 3, the performance in terms of yearly fuel consumption is compared for the three cases. Table-IV provides summary of the three cases in terms of load share of DGs and total FC at the OSV operating points; and the comparative figures in terms of yearly fuel savings in Case-II and Case-III with reference to Case-I. Fig. 7 show the overall SFC and FC for the Case-I, II and III and the difference in FC of Case-II and Case-III with reference to Case-I for discrete values from 680 kW to 9400 kW.

TABLE IV: Performance Comparison of Case-I, II and III for OSV Load Profile

OSV Load Profile				**Case-I**					**Case-II**					**Case-III**					**Case-II wrt Case-I**		**Case-III wrt Case-I**	
Load (%)	Load (kW)	Opt. time (hr/yr)	Opt. time (hr/yr)	PG1 (kW)	PG2 (kW)	PG3 (kW)	PG4 (kW)	FC (kg/yr)	PG1 (kW)	PG2 (kW)	PG3 (kW)	PG4 (kW)	FC (kg/yr)	PG1 (kW)	PG2 (kW)	PG3 (kW)	PG4 (kW)	FC (kg/yr)	FC Savings (ton/yr)	FC Savings (%)	FC Savings (ton/yr)	FC Savings (%)
10	940	16.00	1402	940	0	0	0	212	940	0	0	0	185	940	0	0	0	185	37.5	12.6	37.5	12.6
15	1410	3.00	263	1410	0	0	0	293	1410	0	0	0	278	1410	0	0	0	278	4.0	5.2	4.0	5.2
30	2820	37.75	3307	1410	1410	0	0	586	1410	1410	0	0	556	1006	984	830	0	556	101.3	5.2	101.5	5.2
35	3290	10.0	876	1645	1645	0	0	673	1645	1645	0	0	668	877	828	821	763	649	4.9	0.8	21.7	3.7
50	4700	17.67	1548	2350	2350	0	0	963	2350	2350	0	0	954	1403	1268	1203	826	926	14.5	1.0	57.9	3.9
60	5640	2.08	182	1880	1880	1880	0	1146	1880	1880	1880	0	1145	1443	1423	1414	1361	1111	0.1	0.1	6.3	3.0
75	7050	12.50	1095	2350	2350	2350	0	1445	2350	2350	2350	0	1431	1448	2093	2068	1442	1414	15.3	1.0	33.7	2.1
90	8460	1.00	88	2115	2115	2115	2115	1718	2115	2115	2115	2115	1717	2350	2350	2317	1443	1709	0.1	0.0	0.8	0.5

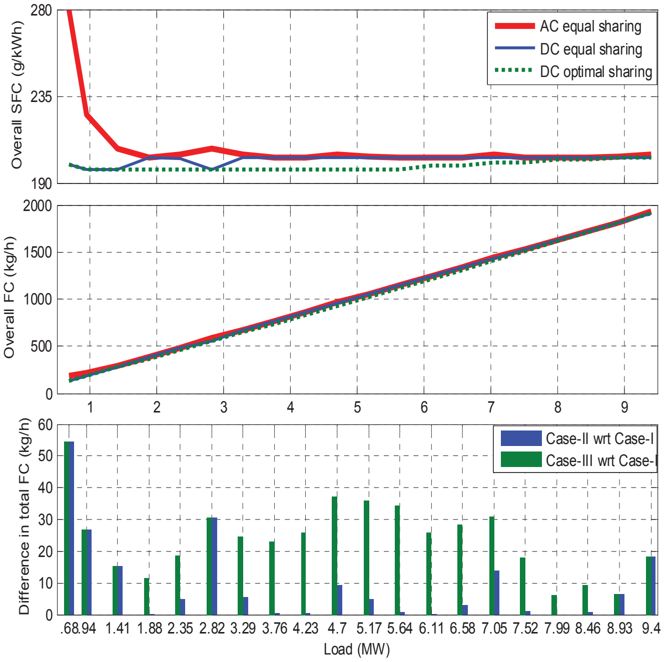

Fig. 7: Comparison of system SFC and system FC against load demand for Case I, Case-II and Case-III

From Table-IV, a difference in FC of 5.2% for Case-II w.r.t. Case-I can be noticed for 1410 kW and 2820 kW demands. There is a significant reduction in FC of up to 12.6% for Case-III with reference to Case-I. In addition, higher fuel savings for the load range 3290-7050 kW can be observed from Fig.7, where the DGs are optimally loaded using PSO algorithm.

VII. CONCLUSIONS

The optimal scheduling of the diesel generators has been carried out using PSO algorithm for minimizing the fuel consumption in a typical OSV application with DC architecture. For accurate SFC modelling, the SFC-vs-load relationships of the diesel engine are characterized using Piecewise Cubic Hermite Interpolating Polynomial interpolation based on the SFC data obtained from the BSFC maps for the entire load range of the engine. Fuel consumption for the load profile of the target OSV is compared for the three cases: Case-I- equal load sharing among DGs in AC architecture; Case-II- equal load sharing among DGs in DC architecture; and Case-III- optimal load sharing among DGs in DC architecture using PSO. An overall fuel saving of 152 ton/year is obtained in Case-II w.r.t. Case-I; and an overall fuel saving of 307 ton/year in Case-III w.r.t. Case-I are obtained. An interesting observation has been made: the number of DGs operating under certain loading are more when scheduled optimally based on PSO as compared to the previous two cases. This means higher availability of power that can be quickly dispatched when required. Furthermore, the PSO algorithm can effectively optimise the response under more complex classification constraints at differing mission points.

VIII. ACKNOWLEDGEMENTS

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REFERENCES

[1] Revised MARPOL Annex VI Regulation 12 “Prevention of Air Pollution from Ships, International Maritime Organization”, Lloyds Register, June 2010.

[2] Srensen A. J., “Marine cybernetics: modeling and control ”, Fifth Ed., UK-05-76, Dept. Marine Technology, NTNU, Trondheim, Norway.

[3] Prousalidis, J.M., Tsekouras, G.J., Kanellos, F., “New challenges emerged from the development of more efficient electric energy generation units ”, Electric Ship Technologies Symposium (ESTS), 2011 IEEE , pp.374,381, 10-13 April 2011.

[4] Hansen, J.F., “Modeling and Control of Marine Power Systems”, PhD thesis, Dept. Eng. Cybernetics, NTNU, Trondheim, Norway, 2000

[5] May, J.J., “Improving Engine Utilization on DP Drilling Vessels,”Dynamic Positioning Conference, Huston, 2003.

[6] Hansen, Jan Fredrik, et al. “Onboard DC Grid for enhanced DP operation in ships,”Dynamic Positioning Conference. Vol. 33. 2011.

[7] MTU Ffiedrichshafen GmbH, “Technical project guide marine applicaton part 1- general,”June 2003.

[8] Yadav, P. , “Analysis, design and optimization of offshore power system network”, PhD thesis, Dept. of ECE, NUS, Singapore, 2013.

[9] Rao S. S., “Engineering Optimization”, 4th Edition, John Wiley and Sons, Inc., 2009.

[10] D. B. Fogel, What is evolutionary computation?, IEEE Spectrum 2000, 37, pp. 2632.

[11] Eberhart, Russell C., and Yuhui Shi. ”Particle swarm optimization: developments, applications and resources.” Evolutionary Computation, 2001. Proceedings of the 2001 Congress on. Vol. 1. IEEE, 2001.