Optimal Shipboard Power Management by Classical and Differential Evolution Methods

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Abstract - *From past few years, optimal electrification of inaccessible offshore systems has become important and received extensive attention from maritime industry. Total electrification of the shipboard power systems known as all-electric ships (AESs) is subjected to introduction of electric propulsion has led to the need for more cost effective solution. With the increasing nature of energy demand in modern ships whether with the growing needs for good energy conservations and environmental protection have intended to pursue AES (All-Electric Ship) configurations. AES is envisioned to become an interesting technology with great potential for both emission and fuel reductions when it is compared with conventional ship power systems. But such on-board systems are inclined to sudden load variations due to fluctuating mission profile as well as weather conditions, thus they have need for effective PMSs (Power Management Systems) to operate optimally under different working environments. Here in this paper, coordinated optimal power management at the supply side of a given All-Electric Ship is studied. This paper proposes a Differential Evolution Algorithm, for Shipboard Power Management. To show the usefulness of the proposed Power Management Systems (PMS), the results are compared with Classical method.*

Key Words**: All-electric ship; constrained optimization; co-ordinated energy management; Power management system.**

1. INTRODUCTION

A ship board electrical system is small in size and has fewer components than a typical commercial power system. A classic combatant ship may have 3 or 4 generators with collective capacity of 80-100 MW. Utmost of this capacity is utilized by propulsion motors, for which a two shaft ship will be rated with the range of 35-40 MW each. These loads are large with respect to the total generating capacity has made the analysis of on-board ship power systems more problematic than commercial power systems. Most of the simplifying assumptions made in the analysis of the commercial power systems are invalid with that of present day ship power systems. This complication requires a detailed model of entire systems including the relevant dynamics of each component.

A reliable supply of electrical power is very essential in these days. With the increasing needs for improved energy conservation, the initiative to pursue an AES (all-electric ship) configuration has emerged [1]. All Electric Ship configuration is expected to change the current ways of power generation, distribution and consumption for the on board energy sub systems and to create a exemplar shift in the processes of control, monitoring and conserving energy through utilizing power for meeting the demand that is propulsion and service loads. Moreover, AES is envisioned to become an interesting technology with a great potential for both emission and fuel reductions in comparison with the typical conventional on-board ship power systems. In an All Electric Ship, the electrical motor driven systems can be substituted with the main diesel propulsion while the required power is provided by various sources such as steam or diesel engines, energy storage systems (ESS), gas turbines (GTs), fuel fells (FCs) and possibly renewable – based prime movers such as PVs (photo voltaic systems), allowing a high efficiency throughout the entire range of operation with respect to vessel speed.

The main challenge with All Electric Ships (AES) is to design and incorporate a PMS (power management system) for optimal scheduling of the on-board isolated ship power plants [3]. Well planned operations of a ship board electrical systems at the supply side (in terms of optimal generator loading), together with the efficient scheduling to meet the loads, in particular electrical propulsion demand, can affect the overall systems efficiency and ensure economic, environmental benefits. PMS can co-ordinate controllable power sources and the loads in a way to meet systems dynamic requirements for short-run intervals.

Power Management Systems can be built on basis of economic dispatch and unit commitment traditional economic load dispatch deals with minimizing power generation cost while satisfying set of equality and inequality constraints. On the other hand, some toxic gasses are emitted polluting environment due to operation of the fossil fuel plants. Thus conventional minimum operation cost cannot be made on the mere basis for generation dispatch, emission minimization to protect environment must also be taken care of.

Many algorithms have been proposed to solve power management problem in shipboard power system.

Classical methods to solve the proposed problem are lambda iteration method, Merit order loading, gradient methods for optimal dispatch and priority list method, dynamic programming methods for optimal combination of units [2]. Apart from these classical methods we have different optimization techniques for the economic operation of generators, which have fast convergence and capability of finding global minimum regardless of initial parameter values. The optimal power management in an All Electric Ship with regard to different objectives and related technical, environmental constraints can be formulated as a mixed –integer nonlinear programming model [4-9]. In this paper optimal management problem can be solved by a heuristic approach using differential evolution.

The DE algorithm is inspired by sociological and biological motivations and can take care of optimality on discontinuous, rough and multi-modal surfaces. Differential Evolution is one of the simple yet powerful population based stochastic optimizer for dealing with variety of optimization problems including multi-modal, constrained, nonlinear, non-differentiable and multi-objective. DE mainly has three advantages, finding the true global minimum regardless of the initial parameter values, fast convergence, and using a few control parameters.

Renewable energy sources, such as photovoltaic energy systems have been increasingly integrated into shipboard power systems and the applications of renewable energy sources has become a global trend. The photovoltaic energy systems on shipboard power systems are installed to produce electricity and will be used to supplement the diesel generators and thus reduce the power required from these units. The proposed PMS performance is analyzed based on a RO-PAX ferry with integrated full electric propulsion and realistic constraints. These results are compared with the results obtained from classical method.

The rest of the paper is structured as follows: Section 2 particularizes on the features of Shipboard power system and Power management along with the technical and environmental constraints, Solution of power management problem in shipboard systems with classical method in Section 3, Section 4 extends to obtain solution of power management problem with differential evolution optimization method, In Section 5, optimal power management problem in shipboard systems including solar PV generation system to meet load along with diesel generating units is discussed , Appendix, Analysis of the results from the proposed PMS applied to AES are presented in Section 6. Finally Section 7 gives the conclusion of the paper.

1.1 LITERATURE REVIEW

Before Power management in offshore systems is very difficult. The main challenges with AES is to design and incorporate a power management system (PMS) for optimal scheduling of the on- board power plants and electrical loads [3].PMS can co-ordinate controllable power sources and loads in a way to meet the system dynamic requirements for short-run intervals. Power management mainly deals with Unit commitment and economic dispatch. The unit commitment in a power system constitutes a study of paramount importance. The study reveals the optimal combination of operating units in a time horizon by considering all the technical and environmental constraints along with meeting the varying demand. Further study and analysis of future expansion, classical methods for unit commitment can be easily analyzed in [1].In this paper the author explains the different classical methods by considering different strategies.

After obtaining the unit status (optimal combination of operating units) we obtain optimal schedule of the power outputs of the operating units which are present at that particular time in order to meet demand. This optimal schedule is called as Economic dispatch. Thus conventional minimum operation cost cannot be the only basis for generation dispatch, emission minimization must also be taken care of. Further study of different classical methods for economic dispatch along with environmental constraints is discussed in [17,18]. In this paper the author explains different methods for economic dispatch considering the technical constraints and environmental constraints. Environmental constraints are very essential to be considered in present day as optimization of total cost along with reduction of pollution is more important [20-22].

Power management system using Particle swarm optimization and dynamic programming was explained in the paper [2]. Whereas the differential evolution algorithm to solve power management problem as explained by authors in [25-29]. In this paper we can see the complete history of differential algorithm and how it is used to solve the power management problem.

2. SHIPBOARD POWER SYSTEMS AND POWER MANAGEMENT

A fully electrified shipboard power system is considered, where generated electric power supplies mainly electric propulsion motors and ship service loads. Ship propulsion is provided by large electric motors driven by power electronic converters that enable continuous shaft variable speed operation in a wide speed range, operational flexibility and fuel economy. Also, the need for large shafts for the coupling of propellers and prime movers and the use of mechanical gearboxes is eliminated [10, 11].

The passage of ‘Clean Air Act Amendments of 1990’and its acceptance by all the nations has forced many utilities to modify their operating strategies in order to meet the rigorous environmental standards set by legislation. Thus the modern operational strategies used in the generating plants now include the reduction of pollution level up to a safe limit set by the environmental regulating authority, in addition to the minimum fuel cost strategy [18-21].

Traditional ships as well as AES must employ a well-designed Ship Energy Efficiency Management Plan (SEEMP) [14]. In the coming future the major targets of SEEMP will be operation cost minimization and gas emission limitation. So far SEEMPs have focused on CO_2 . However, the formulation of the problem can be easily generalized and other pollutants beyond CO_2 can be included in the future. The targets of operation cost minimization and GHG emission limitation might conflict with each other, making the optimal power management in AES a very challenging problem. In this context, if propulsion power is appropriately adjusted in a way to meet AES operation constraints, it could greatly contribute to the limitation of GHG emissions in real time.

In the considered shipboard power system there are five generator units to meet the propulsion and ship service loads [12]. The fuel consumption (FC) of onboard thermal unit may accurately be approximated by a second –order polynomial of its produced power P_i as

$$FC_i(P_i) = c + b.P_i + a.P_i^2 \tag{1}$$

P_i is the power generated, i is i^{th} generator

Objective function

The total variable cost of the power plant(ToC_e) is calculated by taking into account the fuel cost(FC_i), the maintenance cost per power unit(MC_i) and the start-up/shut-down cost(SC_{ij}) of the i-th generator, producing active power P_{ij} during a time interval ΔT_j [25].

$$ToC_e = \sum_{j=1}^{T}\sum_{i=1}^{N_g}(St_{ij}.(SFC_i(P_{ij})) + MC_i).P_{ij}.\Delta T_{ij} + SC_{ij}\left|St_{ij} - St_{i,j-1}\right|) \tag{2}$$

Where T is the total time period under study, SFC_i is the specific fuel consumption, St_{ij} is equal to 1 if unit I is operating, otherwise 0 and N_E is the total number of electric generators.

$$SFC_i(P_i) = FC_i(P_i)/P_i \tag{3}$$

The main objective of the problem is to minimize the total operation cost of AES. This cost minimization should be done subject to several constraints [13].

The technical constraints considered in the cost function minimization while solving power management problem are

(1) Generator loading limits

$$P_{i,\min} < P_{ij} < P_{i,\max} \tag{4}$$

Where, $P_{i,\min}$, $P_{i,\max}$ are minimum and maximum power generating limits of i^{th} generator (MW)

(2) Power balance constraint

$$\sum_{i=1}^{N_g} St_{ij}.P_{ij} = L_j + \Delta P_{prop,j} \tag{5}$$

Subscripts i, j denote i-th generator and j-th time interval, respectively.

(3) Minimum up/down time constraint

$t_{\to OFF,i} - t_{\to ON,i} \geq T_{ON\_\min,i}$ --UP time (6)

$t_{\to ON,i} - t_{\to OFF,i} \geq T_{OFF\_\min,i}$ -Downtime (7)

$t_{\to OFF,i}, t_{\to ON,i}$ are the time points that i-th generator stops or starts operating. $T_{ON\_min,i}$,$T_{OFF\_min,i}$ are minimum allowable operation time and non-operation time of i-th generator.

(4) Blackout prevention constraint

$$\sum_i St_{ij}.P_{i,\max} - L_j - \Delta P_{prop,j} \geq \max\{P_{i,\max}\} \tag{8}$$

max{$P_{i,\max}$} : maximum power of the committed units

(5) Generator ramp rate constraint

$$\frac{\left|P_{ij} - P_{i,j-1}\right|}{\Delta T_j} \leq Rc_{i,\max} \tag{9}$$

Where $Rc_{i,\max}$ is the maximum rate of change of the power produced by the i-th generator.

Apart from the technical constraints considered in the cost function minimization while solving power management problem emission constraint is also considered in order to reduce emissions.

(6) Emission constraint

In order to reduce CO_2 emissions,

$$\frac{\sum_{i=1}^{N_g} c_i.St_{ij}.P_{ij}.SFC_i(P_{ij})}{LF.V_j} \leq EEOI_{\max,sea} \tag{10}$$

$$\frac{\sum_{i=1}^{N_g} c_i.St_{ij}.P_{ij}.SFC_i(P_{ij})}{LF} \leq EEOI_{\max,port}$$

(11)

Where c_i is conversion factor for gas emissions estimation for the i-th generator (gCO_2/gFuel), P_{ij} is Power produced by i-th thermal unit in the j-th time interval (MW), SFCi is Specific fuel consumption of the i-th generator (gFuel/kWh), V_j is Ship speed in the j-th time interval (kn), LF is Ship loading factor (tns).

$EEOI_{max,\ sea}$ is upper limit of EEOI when the ship is travelling and $EEOI_{max,\ port}$ is upper limit of EEOI when the ship is at port.

EEOI

International Maritime Organization (IMO) has promoted a method to assess ship operation efficiency based on the calculation of Energy Efficiency Operation Indicator (EEOI)

EEOI is defined as,

$$EEOI = \frac{mCO_2}{transportwork} \tag{12}$$

Where mCO_2 is the CO_2 mass produced during ship power system operation. EEOI is the ratio of CO_2 mass emitted and the transport work. It indirectly represents ship operational efficiency, as according to the efficiency definition the required consumed energy to produce the relative transport work should be used.CO_2 mass is at an extent proportional to the consumed fuel(energy).Hence, ship operational efficiency and CO_2 emissions are both represented in EEOI in a balanced way [22].

Ship energy efficiency operation indicators $EEOI_s$ and $EEOI_p$ when ship is in the open sea or at port are defined as,

$$EEOI_{s,j} = \frac{mCO_2}{LF.V_j.\Delta T_j} = \frac{\sum_i c_i.P_{ij}.SFC_i(P_{ij})}{LF.V_j} \tag{13}$$

LF is Loading factor

$$EEOI_{p,j} = \frac{mCO_2}{LF.\Delta T_j} = \frac{\sum_i c_i.P_{ij}.SFC_i(P_{ij})}{LF} \tag{14}$$

Ship loading factor LF depends on the type of the examined ship, e.g., passenger ship, RO-PAX ferry, etc. Here, LF is applied to a RO-PAX ferry and it is calculated as,

$$LF = \frac{n'_p.0.1 + n'_v}{n_p.0.1 + n_v} FLD \tag{15}$$

Where, n_p is the maximum number of passengers, n_v is the maximum number of the carried vehicles, n'_p is the number of passengers ,n'_v is the number of carried vehicles and FLD is ship full load displacement (tns).

3. SHIPBOARD POWER MANAGEMENT USING CLASSICAL METHOD

Power management problem in Shipboard power systems can be solved by using Classical methods. In this paper Unit commitment problem is solved by Priority list Method by considering technical constraints. Unit Commitment (UC) is an optimization problem used to determine the operation schedule of the generating units at every time interval with varying loads giving minimum operational cost under different constraints and environments.

Priority of each unit to commit or de-commit before unit scheduling is determined on the basis of unit characteristics. Cost of power produced per unit, of a unit at its maximum output power usually is less than that at any other output power levels.so, it is expected to run a unit at its maximum output power. Priority list is prepared based on fuel cost obtained from the average fuel cost of each unit operating at its maximum output power. The full load average production cost of a unit is defined as the cost per unit of power (Rs/MW) when the unit is operating at its full capacity. Fuel cost of unit is expressed as

$$FC_i = \frac{f_i(P_i^{\max})}{P_i^{\max}} = \frac{a_i}{P_i^{\max}} + b_i + c_i P_i^{\max} \tag{16}$$

The units are ranked by their FC_i in ascending order. Thus, the priority list of units will be formulated based on the order of FC_i, in which a unit with the lowest FC_i will have the highest priority to share the load to be dispatched.

Optimal scheduling of load among the generators is solved by lambda iteration method. The purpose of economic dispatch is to determine the optimal power generation of the units participating in supplying the load. The sum of the total power generation should be equal to the load demand in that particular time. The economic dispatch problems is a constrained optimization problem and it can be mathematically expressed i.e., total production cost

$$C_t = \sum_{i=1}^{n} c_i + b_i P_i + a_i P_i^2 \tag{17}$$

is minimum, subject to constraint.

$$\sum_{i=1}^{n_g} P_i = P_D \tag{18}$$

A typical approach is to augment the constraints into objective function by using the Lagrange multipliers

$$L_i = C_t + \lambda(P_D - \sum_{i=1}^{n_g} P_i) \tag{19}$$

The minimum of this unconstrained function is found at the point where the partials of the function to its variables are zero.

$$\frac{\partial L}{\partial P_i} = 0 \tag{20}$$

From the above equation the condition for optimum dispatch can be obtained as

$$\frac{dC_i}{dP_i} = \lambda \tag{21}$$

i=1,2,………,ng, which results in

$$b_i + 2a_i P_i = \lambda \tag{22}$$

P_i can be calculated as

$$P_i = \frac{\lambda - b_i}{2a_i} \tag{23}$$

After obtaining the optimal schedule of powers we check for power balance constraint, generator loading limits of units which are operating in that time interval and generator ramp up/down rates for calculating total cost.

Methodology

The procedure for implementing Shipboard Power Management using classical method is given below

Step 1: Specify the minimum and maximum generator loading limits of each unit. Specify the fuel cost of each unit, load even.

Step 2: Determine the full load average production cost of each unit and arrange them in ascending order (as in Priority list).

Step 3: Obtain optimal combination of units for the load in that particular time interval. Optimal combination of units (unit status) is obtained by following priority list scheme.

Step 4: Check if any violations in blackout prevention constraint, minimum up/down time constraint for the optimal unit status generated.

Step 5: If there are any violations repair the system until the constraints are satisfied and obtain a set of optimal combination.

Step 6: Specify the load requirement in each time interval.

Step 7: Distribute the Powers to be generated in order to meet the load in that time interval, among the operating units at that time (which we know from the unit status obtained).

Step 8: Optimal combination of power output (economic dispatch) of all generating units which are operating in that time interval is obtained by using Lambda Iteration Method.

Step 9: Check for the technical and environmental constraints and repair if any violations.

Step 10: Calculate total cost from the objective function which includes fuel cost, startup/shut-down cost and maintenance cost.

4. SHIPBOARD POWER MANAGEMENT USING DIFFERENTIAL EVOLUTION

The solution for power management in Shipboard power systems aims to optimize a selected objective function with subject to different technical and environmental constraints [23]. Mathematically, the power management problem can be formulated as mentioned in Section II.

Differential Evolution

Generally, most of the classical methods of optimization apply sensitivity analysis and gradient based algorithms by linearizing the objective function and the system constraints around an operating point. Unfortunately, the Optimal Power management problem is a nonlinear and is formulated as mixed-integer nonlinear optimization problem. Hence, classical optimization techniques are not suitable for such problem. Moreover, there is no approach to decide whether a local optimum is also the global optimum. Therefore, conventional optimization methods that make use of derivatives and gradients may not be able to identify the global optimum [26-28].

Recently, evolutionary optimization techniques have been used to solve Power management problem to overcome the limitations of classical optimization techniques. A wide variety of heuristic optimization techniques have been applied such as genetic algorithm (GA), simulated annealing (SA), tabu search, and particle swarm optimization(PSO). The results reported in the literature were promising and encouraging for further research in this direction.

In 1995, K.Price and R.Storn proposed a floating point encoded evolutionary algorithm for global optimization and named it differential evolution (DE) algorithm owing to a special kind of differential operator, which they invoked to create new off-spring from parent chromosomes instead of classical crossover or mutation. Similar to GA, DE (differential evolution) algorithm is a population based algorithm that uses crossover, mutation and selection operators. The key differences between GA and DE algorithm are selection process and mutation scheme that makes DE self-adaptive.

Differential Evolution is one of the simple yet powerful population based stochastic optimizer for dealing with variety of optimization problems including multi-modal, constrained, nonlinear, non-differentiable and multi-objective. The standard DE algorithm has been competitive in solving global optimization problems over continuous spaces. Due to its simplicity, robustness and effectiveness, it has been successfully applied in various scientific and engineering fields.

Moreover, there are only few control parameters used to update the population of DE, thus it is easy for implementation and parameter tuning. The mutation operator, the crossover operator and the selection operator are the three main evolutionary operators, commonly applied in DE to update the population. First two operators (the mutation operator and the cross-over operator) are used to generate the trial vectors, and the third operator (the selection operator) determines the better one between the target vector and its trial vector for the next generation based on their fitness values. The standard DE algorithm and most of its improved variants have operated on real values. However, the UCP in power systems is dealing with 0-1, binary variables which represents on/off schedule of the thermal generating units in each time-period of planning horizon [24].

The main features of the DE algorithm can be stated as follows:

1) Like any other evolutionary algorithm, DE starts with a population size of NP individuals where the individuals are D-dimensional variable vectors.

2) The subsequent generations will be represented by discrete time steps like t=0,1,2,………,t,t+1,etc

3) Since the vectors are likely to be changed over different generations, the following notation may be adopted for representing the ith vector of the population at the current generation (i.e. at time t):

$$\vec{X_i}(t) = [x_{i,1}(t), x_{i,2}(t), \; . \; . \; . \; . \; , x_{i,D}(t)]$$

This vector is referred to as 'genome', 'individual' or 'chromosome'.

4) Several optimization parameters must also be tuned. These parameters are joined together under the common name of control parameters. As a matter of fact, there are only three real control parameters in the algorithm, which are:

(a) Differentiation (or mutation) constant F,

(b) Crossover constant CR, and

(c) Population size NP.

(d) Dimension of problem D that scales the difficulty of the optimization task;

(e) Maximal number of generations (or iterations) GEN, which may serve as a stopping condition;

(f) Low and high boundary constraints of variables that limit the feasible area.

DE Algorithm flow

```
Generate the initial population of size NP
Do while
    For each individual, j, in the population
        Generate three random integers $r_1, r_2, r_3 \in (1, NP), with\ r_1 \neq r_2 \neq r_3 \neq j$
        Generate a random integer $i_{rand} \in (1, n)$
        For each parameter i
            $y^{i,g} = x^{r1,g} + F(x^{r2,g} - x^{r3g})$
            $z_j^{i,g} = \begin{cases} y_j^{i,g} & if\ rand(\quad) \leq CR\ or\ j = j_{rand} \\ x_j^{i,g} & otherwise \end{cases}$
        End for
        Replace $x^{i,g}$ with the child $z^{i,g}$ if $z^{i,g}$ is better
    End for
Until the termination condition is achieved
```

Methodology

The procedure for implementing Shipboard Power Management by using Differential Evolution is given below

Step 1: Specify the minimum and maximum generator loading limits of each unit.

Step 2: Obtain the Unit status randomly. Units are randomly committed by considering a variable h, whose value is assigned by rand () function. Range of the rand () function to be (0,1). If the value assigned for h is more than 0.5 then we consider the unit to be 1(ON). If the value assigned for h is less than 0.5 then we consider the unit to be 0(OFF).

Step 3: Check for the Blackout prevention constraint and minimum up/down time constraint by following the repair algorithms.

Step 4: Unit status is updated if any constraints are violated by using repair strategies employed respectively.

Step 5: For this updated unit status, obtain the optimal schedule of power outputs (economic dispatch) in order to get optimum cost.

Step 6: Check for the power balance constraint, generator power limits and ramp rate limits of generating units.

Step 7: If there are any violations in the constraints go to repair strategy to satisfy them.

Step 8: Calculate total cost and fitness from the objective function which includes fuel cost, startup/shut-down cost and maintenance cost.

Step 9: Create a new population by using differential evolution and calculate cost which satisfies all the technical and environmental constraints.

Step 10: By following the DE cycle of mutation, cross-over and selection obtain the best set of schedule.

Step 11: Obtain the optimal cost by using this optimal schedule of power outputs from DE (as the control variable is power).

Step 12: Check whether all the constraints are satisfied and thus obtained cost is the best cost.

5. SHIPBOARD POWER MANAGEMENT WITH PV USING DE

Apart from solving Power management problem in Ship power system and obtaining the Optimum cost by using the proposed Differential evolution algorithm, we are incorporating PV to reduce the use of fossil fuels and to reduce emissions. As the present day world is moving on to renewables for generation of electricity, we have considered solar as one of the reliable source of energy. A PV system or solar power generation system is a power system designed to supply solar power which is usable by means of photovoltaics. Designing reliable and effective PV systems requires understanding both the art and science of photovoltaics and applying the strategies, skills and techniques necessary to meet specific goals and objectives. It consists of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to convert output from direct to alternating current [29, 30].

Here we are installing three PV generating units of 100KW capacity each. We consider half of the PV generation (0.15MW) in one case and perform the optimal power scheduling with DE to solve power management problem. We consider full generation capacity from PV (0.3MW) in another case and perform the optimal power scheduling with DE to solve power management problem.

Methodology

The procedure for implementing Shipboard Power Management with PV using Differential Evolution is given below

Step 1: The power generation from PV (solar) is considered to be some value.

Step 2: At each time interval load can be considered as the difference of the total load and the power generated from solar in that particular time horizon.

Step 3: Specify thus obtained load for the Optimal combination of units and Optimal schedule of power generation among the operating units.

Step 4: Check for any violations in technical and environmental constraints and repair them.

Step 5: Rest of the procedure for obtaining optimal combination and optimal schedule which results in optimum cost and fitness follows the steps as in DE

6. ANALYSIS OF RESULTS

The proposed optimization method is applied on RO-PAX ferry with five generators supplying two electric propulsion motors. The power management problem in ships is solved by using Classical method and Differential evolution method. Optimal power scheduling obtained from classical method is presented in Fig. 1.

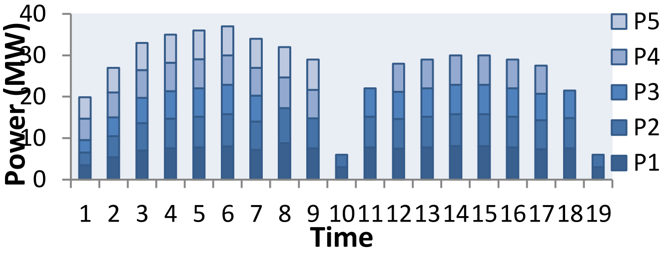


Fig. 1 Power generation schedule by classical method

Optimal power generation scheduling by DE method is presented in Fig. 2

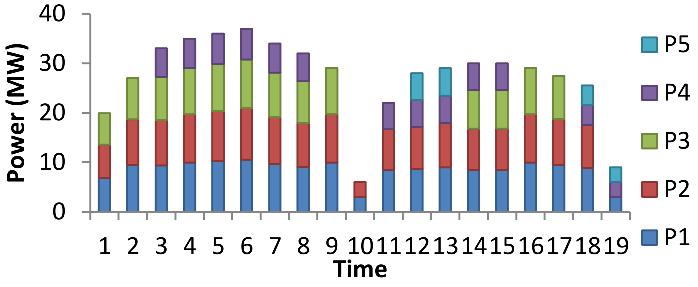


Fig. 2 Power generation schedule by DE method

Convergence characteristics of the cost function by DE is shown in Fig.3

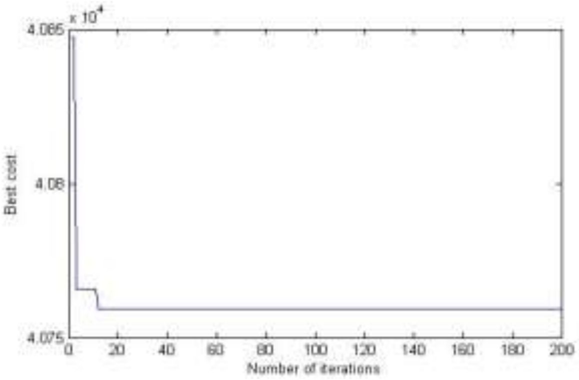
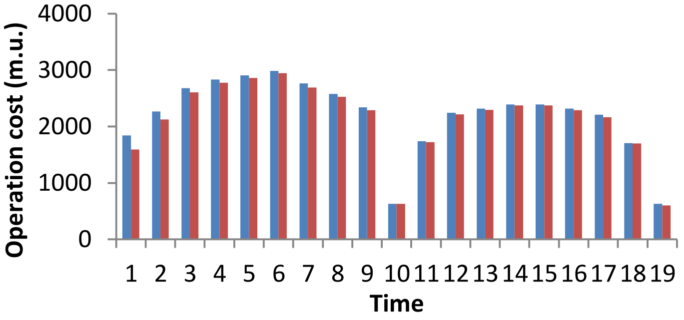


Fig.3 Convergence of cost function using DE

Operation cost during all time intervals obtained by Classical and DE are presented in Fig. 4



Blue: Classical, Red: DE

Fig. 4 Operating cost by both Classical and DE method

CASE 1

Optimal power generation scheduling with PV (0.15MW) using DE is shown in Fig. 5 and Convergence characteristics of cost function with PV (0.15MW) using DE is shown in Fig. 6. Operation cost during all the intervals obtained by DE and DE with PV (0.15MW) is presented in Fig. 7.

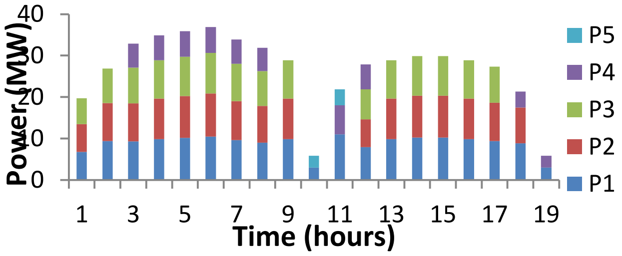


Fig. 5 Power generation schedule with PV (0.15MW) using DE

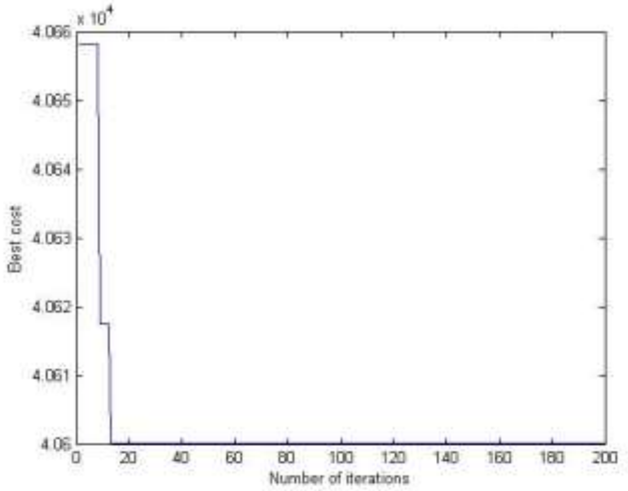


Fig. 6 Convergence of cost function with PV (0.15MW) using DE

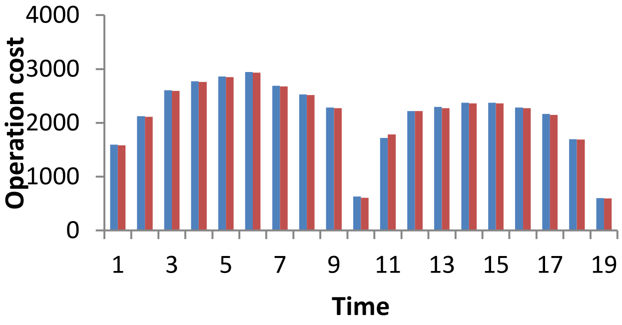


Fig. 7 Operation cost by DE and DE with PV (0.15MW)

CASE 2

Optimal power generation scheduling with PV (0.3MW) using DE is shown in Fig. 8 and Convergence characteristics of cost function with PV (0.3MW) using DE is shown in Fig. 9. Operation cost during all the intervals obtained by DE and DE with PV (0.3MW) is presented in Fig. 10.

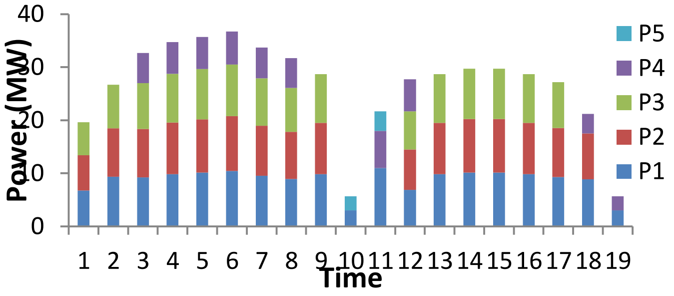


Fig. 8 Power generation schedule with PV (0.3 MW) using DE

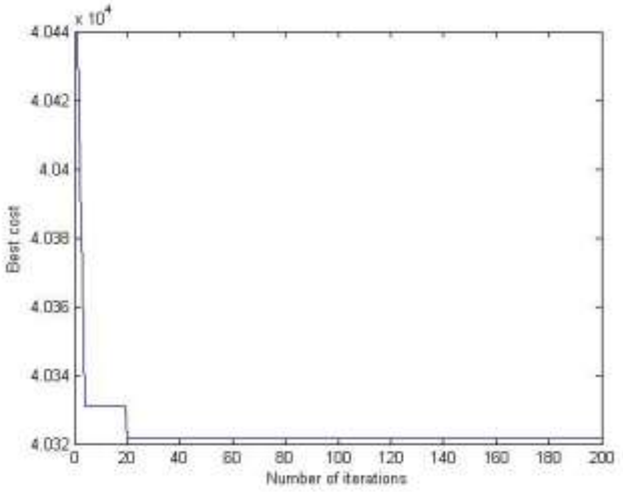


Fig. 9 Convergence of cost function with PV (0.3 MW) using DE

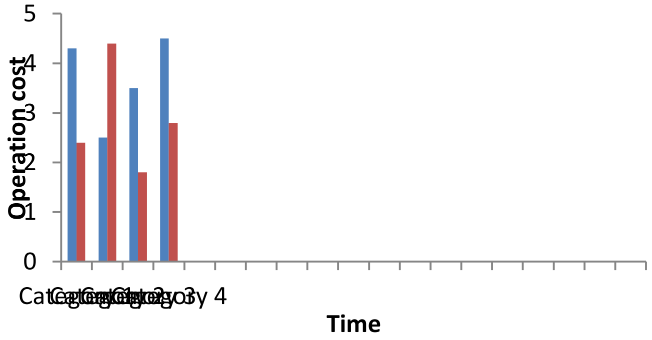


Fig. 10 Operation cost by DE and DE with PV (0.3 MW)

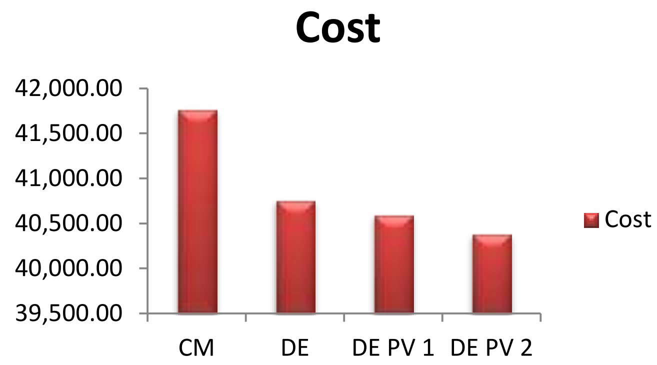


Fig. 11 Operation cost by Different Methods

Appendix

The technical parameters of the ship and the onboard power system are presented here. Ship parameters depends on the type of ship,e.g., passenger ship, RO-PAX ferry. Here we have considered RO-PAX ferry comprising two large electric propulsion motors supplied by a set of five electrical generators.

Table 1 Cost coefficients of generating units

Generator number	a	B	c
1	5.40	61.5	390
2	5.40	63	400
3	5.60	65	420
4	13.1	12	430
5	13.5	10	450

Table 2 Ship parameters

PARAMETER	SPECIFICATION
TYPE	RO-PAX ferry
Nominal speed (kn)	24
Maximum no of passengers	2500
No of vehicles (nv)	700
Full Load Displacement (tns)	70,000
EEOImaxs (gCO2/tn.kn)	27.5
EEOImaxp (gCO2/tn.kn)	165

Table 3 Data for Ship pay load

Part of the Examined Route	Number of Passengers, n_{P1}	Number of vehicles, n_{V1}	Ship Loading Factor, LF (tns)
Departure-Intermediate port	1955	600	58,616
Intermediate port-Final destination	1720	500	49515

Table 4 Parameters of units

PARAMETERS	GEN 1	GEN 2	GEN 3	GEN 4	GEN 5
Minimum UP time (Hours)	1	1	1	1	1
Minimum DOWN time (Hours)	1	1	1	1	1
Start-up/Shut-down cost (m.u.)	0	0	0	0	0
CO_2 emissions (gCO_2/g fuel)	3.20	3.20	3.20	2.50	2.50
Ramp up rate	8	8	2	1	1
Ramp down rate	7	7	2	1	0

Table 5 Power Generation limits of units

PARAMETERS	GEN 1	GEN 2	GEN 3	GEN 4	GEN 5
Technical maximum power (MW)	15	15	15	9	9
Technical minimum power(MW)	3	3	3	2	2
Nominal power (MW)	15	15	15	9	9

Ship power systems are prone to sudden load variations due to the changing weather conditions as well as mission profile. Ship load (MW) during all the time intervals and Ship speed during the entire route travelled according to time interval during the complete route travelled is in Table 6.

Table 6 Ship Load data and speed

Time interval	Load (MW)	Speed (kn)
1	19.9	17
2	27	19

3	33	20.5
4	35	21.2
5	36	21
6	37	22.5
7	34	22
8	32	20.5
9	29	19.8
10	6	0
11	22	17.5
12	28	18.5.
13	29	19.8
14	30	20.2
15	30	20
16	29	20.2
17	27.5	18
18	21.5	17
19	6	0

7. CONCLUSIONS

From the results it can be concluded that Power management problem in ship power systems comprises of UCP and optimal scheduling. Unit commitment problem and optimal power scheduling (economic dispatch) problem is solved by using Differential evolution method and Classical method. Operating cost is calculated by satisfying all the technical constraints. The total operation cost obtained by classical method is 41,770.4986, whereas the total operation cost obtained by differential evolution optimization method is 40,759.4049.

Table 7 Data for Installation of PV (100 KW capacity)

Capacity of Power Plant	100KW
Generation per year	2,70,000
Cost of Electricity per unit	Rs.1.8
Investment Cost per MW	68 Lakhs
Operation and Maintenance cost per year	60,000
Payback period	25 years

Thus we can observe the optimum cost obtained by DE method is smaller when compared with classical method by 2.42%. The load sharing of generating units is analyzed and presented under Case study and discussion section. Operation cost with respect to time horizon is calculated and is presented in section VI. Emission constraint is also been satisfied. In order to obtain optimal power management, power is generated by incorporating PV system. The results are been analyzed by considering the PV generation of 0.15MW in one case and 0.3MW in another case. The total operation cost has been reduced by 0.39% in case of 0.15MW PV generation using DE and the cost is 40,600.0917 in comparison with DE method. The total operation cost has been reduced by 0.91% in case of 0.3MW PV generation using DE and the cost is 40,386.5387 in comparison with DE method. By this analysis we can conclude integration of PV generation system in ship power system is advantageous and reduces the emissions apart from cost optimization.

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