Combined Economic and Multiple Emissions Optimization Considering Third Order Polynomials Using Grasshopper Optimization Algorithm

Karthikeyan. R, Subramanian. S, Elanchezhian. E. B

Abstract: ***The power system desires to gratify its customers demand with minimum cost and emission. Fuel cost and emission has directly association with energy cost. The objective of this work is to trace the most effective generator schedule which minimizes both fuel cost and multiple emission pollutants such as SO_2, NO_x and CO_2 simultaneously. This paper presents grasshopper optimization algorithm for solving economic multiple emissions dispatch problem including multiple pollutants expressed as third order polynomials. The simulation analyses are carried out on standard six unit test system to show the effectualness of the presented method. The analyses are performed for the above mentioned test system through five different scenarios such as fuel cost minimization, multiple emissions minimization, combined multiple emissions minimization, combined economic emission dispatch and combined economic multiple emissions dispatch. Numerical simulation results on an illustrative system depicts that, the proposed approach has less convergence time, and good performance when compared to the recently heuristic approaches. The results thus indicate that the proposed model achieves a more accurate estimate of fuel cost and emission in the system and can be effectively utilized for cost and emission analysis in power system applications.***

Index Terms**: CEED, CEMED, CO_2, Emission, Fuel cost, GOA, NO_X, Price penalty factor, SO_2, Total cost.**

I. INTRODUCTION

Energy is essential to run industrial and domestic life. In the process of production of energy for various industrial and domestic purposes certain flue gasses are emitted. This will increase the level of toxicity in the air. The earth gets heated and polluted. As one of the preventive measure, the emission level of CO_2, NO_X and SO_2 has to be abruptly reduced and simultaneously the generation cost should be reduced.

In the literature review generally three different approaches of Economic dispatch problems draws more consideration. First, the single objective economic dispatch [1, 2] which minimizes the fuel cost subjected to various constraints is dealt. Secondly, the emission dispatch [3] of single environmental pollutant is carried out. Thirdly, the solution is searched for combined economic emission dispatch (CEED) [4]. In this paper, the combined economic multiple emission dispatch (CEMED) problem considering three different emission pollutants expressed in cubic function form is solved in addition to conventional economic dispatch, multiple emissions dispatch, combined multiple emissions dispatch and economic multiple emissions dispatch problem.

This CEMED problem is one of the multi-objective optimization problems. One way of solving multi-objective problem is to transform the multi-objective problem into single objective optimization problem, by applying price penalty factors (h). In the extensive literature researches that have been done, the multi-objective ED problem is solved by various types of price penalty factors in the literature [5-12]. The price penalty factors $h_{max\text{-}min}$ and $h_{min\text{-}min}$ are considered for the first time in blending the cost and emission expressed in cubic form in this article for solving the multi-objective dispatch problem. In the present study, six different penalty factors helps to solve CEMED problem in which minimum cost and the diffusion of CO_2, NO_X and SO_2 have been handled together as single objective optimization problem. Often the researchers apply various price penalty factors to optimize CEMED problem and this study will help to choose more suitable penalty factor among various price penalty factors for CEMED problems. Further, this study uncovers the aspects of various price penalty factors which will benefit the policy maker to implement more economical and eco friendly power generation system. The grasshopper optimization algorithm (GOA) [13-15] has been used for the solution of transformed combined economic multiple emission dispatch problem. In this study, GOA has been applied to CEMED with cubic cost functions for the first time in literature. The comparative results with some of the recent published methods confirm the reliability of the proposed strategy to find the accurate and feasible optimal solutions for practical ED problems.

II. PROBLEM FORMULATIONS

The objective of CEMED problem is to minimize the four incompatible objective functions which include cubic fuel cost function, SO_2, NO_X and CO_2 emission functions, satisfying the equality and inequality constraints. The problem formulations of various economic dispatch (ED) problems are as follows:

2.1 Fuel Cost Minimization

The fuel costs of the conventional generators represented by cubic polynomial can be mathematically formulated as

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Karthikeyan. R , Lecturer (Assistant Professor deputed from Annamalai University), Alagappa Government Polytechnic College, Karaikudi, India.

Subramanian. S, Professor, Annamalai University, Annamalainagar, India.

Elanchezhian. E. B, Lecturer (Assistant Professor deputed from Annamalai University), Government Polytechnic College, Srirangam, India.

$$F_c = \sum_{i=1}^{N} \left(a_i P_i^3 + b_i P_i^2 + c_i P_i + d_i \right) \left(\frac{\$}{h} \right) \qquad (2.1)$$

where F_C is fuel cost, P_i is real power generation of unit i, a_i, b_i, c_i, d_i is cost coefficients of generating unit i and N is number of generating units.

2.2 Multiple Emissions Dispatch

The noxious gases released by thermal generating units due to the burning of fossil fuel sources such as SO_2, NO_X and CO_2 can individually contribute to the total global pollutants emissions. The emission dispatch minimizes the release of these harmful gases in the atmosphere. The emission dispatch function is also represented by cubic polynomial and can be mathematically formulated as follows.

$$\mathrm{E}_{SO_2} = \sum_{i=1}^{N} \left(\alpha_{SO_2 i} P_i^3 + \beta_{SO_2 i} P_i^2 + \eta_{SO_2 i} P_i + \gamma_{SO_2 i} \right) \left(\frac{kg}{h} \right) \qquad (2.2)$$

$$\mathrm{E}_{NO_x} = \sum_{i=1}^{N} \left(\alpha_{\mathrm{NO}_x i} P_i^3 + \beta_{\mathrm{NO}_x i} P_i^2 + \eta_{\mathrm{NO}_x i} P_i + \gamma_{\mathrm{NO}_x i} \right) \left(\frac{kg}{h} \right) \qquad (2.3)$$

$$\mathrm{E}_{CO_2} = \sum_{i=1}^{N} \left(\alpha_{CO_2 i} P_i^3 + \beta_{CO_2 i} P_i^2 + \eta_{CO_2 i} P_i + \gamma_{CO_2 i} \right) \left(\frac{kg}{h} \right) \qquad (2.4)$$

where E_{SO2} is total sulphur-dioxide emission and α_{SO2i}, β_{SO2i}, η_{SO2i}, γ_{SO2i} are sulpur-dioxide emission coefficients of the generating unit i, E_{NOX} is total nitrogen oxide emission and α_{NOXi}, β_{NOXi}, η_{NOXi}, γ_{NOXi} are nitrogen oxide emission coefficients of the generating unit i, E_{CO2} is total carbon-dioxide emission and α_{CO2i}, β_{CO2i}, η_{CO2i}, γ_{CO2i} are carbon-dioxide emission coefficients of the generating unit i.

2.3 Combined Multiple Emissions Dispatch

Each generating units emits SO_2, NO_X and CO_2 pollutants as emissions. The total emission emitted by thermal generating units can be calculated by combined multiple emissions dispatch problem formulated as follows.

$$\mathrm{E}_T = E_{SO_2} + E_{NOx} + E_{CO_2} \qquad (2.5)$$

2.4 Combined Economic Emission Dispatch

As discussed above, the economic dispatch and emission dispatch are complete two different objectives. It is necessary to arrive at a compromised solution which can attain both minimized fuel cost and emitting least amount of pollutants in the atmosphere, by creating a multi-objective problem combining (2.1), (2.2), (2.3) and (2.4) with the help of penalty factor "*h*". The penalty factor acts as an intermediate to reform the emission criteria into an equivalent fuel cost for the emission. Mathematically, the price penalty factor is associated with each emission coefficients which transforms two differently aimed single objective function to a CEED problem. The various price penalty factors are formulated and calculated in later section of this article. The combined economic emission dispatch problem considering SO_2, NO_X and CO_2 pollutants independently can be mathematically stated as:

$$F_{Tso_2} = \sum_{i=1}^{N} \begin{matrix} \left(a_i P_i^3 + b_i P_i^2 + c_i P_i + d_i \right) + \\ h_{so_2 i} \left(\alpha_{so_2 i} P_i^3 + \beta_{so_2 i} P_i^2 + \eta_{so_2 i} P_i + \gamma_{so_2 i} \right) \end{matrix} \left(\frac{\$}{h} \right) \qquad (2.6)$$

$$F_{TNo_x} = \sum_{i=1}^{N} \begin{matrix} \left(a_i P_i^3 + b_i P_i^2 + c_i P_i + d_i \right) + \\ h_{No_x i} \left(\alpha_{No_x i} P_i^3 + \beta_{No_x i} P_i^2 + \eta_{No_x i} P_i + \gamma_{No_x i} \right) \end{matrix} \left(\frac{\$}{h} \right) \qquad (2.7)$$

$$F_{Tco_2} = \sum_{i=1}^{N} \begin{matrix} \left(a_i P_i^3 + b_i P_i^2 + c_i P_i + d_i \right) + \\ h_{co_2 i} \left(\alpha_{co_2 i} P_i^3 + \beta_{co_2 i} P_i^2 + \eta_{co_2 i} P_i + \gamma_{co_2 i} \right) \end{matrix} \left(\frac{\$}{h} \right) \qquad (2.8)$$

where F_{TSO2} is total cost of CEED considering SO_2 emission, F_{TNOX} is total cost of CEED considering NO_x emission and F_{TCO2} is total cost of CEED considering CO_2 emission.

2.5 Combined Economic Multiple Emission Dispatch (CEMED)

To investigate the combined impact of SO_2, NO_X and CO_2 pollutants, the Combined Economic Multiple Emission Dispatch is carried out considering all 3 pollutants jointly at the same power demand and are formulated as

$$F_{T-SO2-NOx-CO2} = \sum_{i=1}^{\mathrm{N}} \begin{bmatrix} \left(a_i P_i^3 + b_i P_i^2 + c_i P_i + d_i \right) + \\ h_{so_2 i} \left(\alpha_{so_2 i} P_i^3 + \beta_{so_2 i} P_i^2 + \eta_{so_2 i} P_i + \gamma_{so_2 i} \right) + \\ h_{No_x i} \left(\alpha_{No_x i} P_i^3 + \beta_{No_x i} P_i^2 + \eta_{No_x i} P_i + \gamma_{No_x i} \right) + \\ h_{co_2 i} \left(\alpha_{co_2 i} P_i^3 + \beta_{co_2 i} P_i^2 + \eta_{co_2 i} P_i + \gamma_{co_2 i} \right) \end{bmatrix} \left(\frac{\$}{h} \right) \qquad (2.9)$$

2.6 Various price penalty factors for CEMED problem

The existing literature proposes four different price penalty factors $h_{min-max}$, $h_{max-max}$, $h_{average}$ and h_{common} [7] to solve CEMED problem. Additionally two more price penalty factors $h_{max-min}$ and $h_{min-min}$ are proposed in this article to solve the CEMED problem considering cubic fuel cost and emission functions. The following are the equations for the above mentioned penalty factors

2.6.1 Min-Max ($h_{min-max}$) Price penalty factor

$$h_{so_2 i} = \frac{\left(a_i P_{\min}^3 + b_i P_{\min}^2 + c_i P_{\min} + d_i \right)}{\left(\alpha_{so_2 i} P_{\max}^3 + \beta_{so_2 i} P_{\max}^2 + \eta_{so_2 i} P_{\max} + \gamma_{so_2 i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.10)$$

$$h_{No_x i} = \frac{\left(a_i P_{\min}^3 + b_i P_{\min}^2 + c_i P_{\min} + d_i \right)}{\left(\alpha_{Noxi} P_{\max}^3 + \beta_{No_x i} P_{\max}^2 + \eta_{No_x i} P_{\max} + \gamma_{No_x i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.11)$$

$$h_{co_2 i} = \frac{\left(a_i P_{\min}^3 + b_i P_{\min}^2 + c_i P_{\min} + d_i \right)}{\left(\alpha_{co_2 i} P_{\max}^3 + \beta_{co_2 i} P_{\max}^2 + \eta_{co_2 i} P_{\max} + \gamma_{co_2 i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.12)$$

where h_{SO2i} = Price penalty factor of SO_2 min-max emission, h_{NOXi} = Price penalty factor of NO_X min-max emission, h_{CO2i} = Price penalty factor of CO_2 min-max emission.

2.6.2 Max- Max ($h_{max-max}$) Price penalty factor

$$h_{so_2 i} = \frac{\left(a_i P_{\max}^3 + b_i P_{\max}^2 + c_i P_{\max} + d_i \right)}{\left(\alpha_{so_2 i} P_{\max}^3 + \beta_{so_2 i} P_{\max}^2 + \eta_{so_2 i} P_{\max} + \gamma_{so_2 i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.13)$$

$$h_{No_x i} = \frac{\left(a_i P_{\max}^3 + b_i P_{\max}^2 + c_i P_{\max} + d_i \right)}{\left(\alpha_{Noxi} P_{\max}^3 + \beta_{No_x i} P_{\max}^2 + \eta_{No_x i} P_{\max} + \gamma_{No_x i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.14)$$

$$h_{co_2 i} = \frac{\left(a_i P_{\max}^3 + b_i P_{\max}^2 + c_i P_{\max} + d_i \right)}{\left(\alpha_{co_2 i} P_{\max}^3 + \beta_{co_2 i} P_{\max}^2 + \eta_{co_2 i} P_{\max} + \gamma_{co_2 i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.15)$$

where h_{SO2i} = Price penalty factor of SO_2 max-max emission, h_{NOXi} = Price penalty factor of NO_X max-max emission, h_{CO2i} = Price penalty factor of CO_2 max-max emission.

2.6.3 Max-Min ($h_{max-min}$) Price penalty factor

$$h_{so_2 i} = \frac{\left(a_i P_{\max}^3 + b_i P_{\max}^2 + c_i P_{\max} + d_i \right)}{\left(\alpha_{so_2 i} P_{\min}^3 + \beta_{so_2 i} P_{\min}^2 + \eta_{so_2 i} P_{\min} + \gamma_{so_2 i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.16)$$

$$h_{No_x i} = \frac{\left(a_i P_{\max}^3 + b_i P_{\max}^2 + c_i P_{\max} + d_i \right)}{\left(\alpha_{Noxi} P_{\min}^3 + \beta_{No_x i} P_{\min}^2 + \eta_{No_x i} P_{\min} + \gamma_{No_x i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.17)$$

$$h_{co_2 i} = \frac{\left(a_i P_{\max}^3 + b_i P_{\max}^2 + c_i P_{\max} + d_i \right)}{\left(\alpha_{co_2 i} P_{\min}^3 + \beta_{co_2 i} P_{\min}^2 + \eta_{co_2 i} P_{\min} + \gamma_{co_2 i} \right)} \left(\frac{\$}{kg} \right) \qquad (2.18)$$

where h_{SO2i} = Price penalty factor of SO_2 max-min emission, h_{NOXi} = Price penalty factor of NO_x max-min emission, h_{CO2i} = Price penalty factor of CO_2 max-min emission.

2.6.4 Min-Min ($h_{min\text{-}min}$) Price penalty factor

$$h_{so_2i} = \frac{\left(a_iP_{\min}^3 + b_iP_{\min}^2 + c_iP_{\min} + d_i\right)}{\left(\alpha_{so_2\,i}P_{\min}^3 + \beta_{so_2\,i}P_{\min}^2 + \eta_{so_2\,i}P_{\min} + \gamma_{so_2\,i}\right)}\left(\frac{\$}{kg}\right) \quad (2.19)$$

$$h_{No_xi} = \frac{\left(a_iP_{\min}^3 + b_iP_{\min}^2 + c_iP_{\min} + d_i\right)}{\left(\alpha_{Noxi}P_{\min}^3 + \beta_{No_x\,i}P_{\min}^2 + \eta_{No_x\,i}P_{\min} + \gamma_{No_x\,i}\right)}\left(\frac{\$}{kg}\right) \quad (2.20)$$

$$h_{co_2i} = \frac{\left(a_iP_{\min}^3 + b_iP_{\min}^2 + c_iP_{\min} + d_i\right)}{\left(\alpha_{co_2\,i}P_{\min}^3 + \beta_{co_2\,i}P_{\min}^2 + \eta_{co_2\,i}P_{\min} + \gamma_{co_2\,i}\right)}\left(\frac{\$}{kg}\right) \quad (2.21)$$

where h_{S02i} = Price penalty factor of SO_2 min-min emission, h_{NOXi} = Price penalty factor of NO_X min-min emission, h_{CO2i} = Price penalty factor of CO_2 min-min emission.

2.6.5 Average ($h_{average}$) Price penalty factor

$$h_{So_2i} = \frac{\begin{array}{c}\left|F_c(P_{\min i})/E_{So_2}(P_{\max i})\right| + \left|F_c(P_{\max i})/E_{So_2}(P_{\max i})\right| + \\ \left|F_c(P_{\max i})/E_{So_2}(P_{\min i})\right| + \left|F_c(P_{\min i})/E_{So_2}(P_{\min i})\right|\end{array}}{4}\left(\frac{\$}{kg}\right) \quad (2.22)$$

$$h_{No_xi} = \frac{\begin{array}{c}\left|F_c(P_{\min i})/E_{No_x}(P_{\max i})\right| + \left|F_c(P_{\max i})/E_{No_x}(P_{\max i})\right| + \\ \left|F_c(P_{\max i})/E_{No_x}(P_{\min i})\right| + \left|F_c(P_{\min i})/E_{No_x}(P_{\min i})\right|\end{array}}{4}\left(\frac{\$}{kg}\right) \quad (2.23)$$

$$h_{Co_2i} = \frac{\begin{array}{c}\left|F_c(P_{\min i})/E_{Co_2}(P_{\max i})\right| + \left|F_c(P_{\max i})/E_{Co_2}(P_{\max i})\right| + \\ \left|F_c(P_{\max i})/E_{Co_2}(P_{\min i})\right| + \left|F_c(P_{\min i})/E_{Co_2}(P_{\min i})\right|\end{array}}{4}\left(\frac{\$}{kg}\right) \quad (2.24)$$

where h_{SO2i} = Average price penalty factor of SO_2 emission, h_{NOXi} = Average price penalty factor of NO_X emission, h_{C02i} = Average price penalty factor of CO_2 emission.

2.6.6 Common (h_{common}) Price penalty factor

$$h_{So_2i} = \frac{\sum_{i=1}^{N} h_{Average_{So_2i}}}{n}\left(\frac{\$}{kg}\right) \quad (2.25)$$

$$h_{No_xi} = \frac{\sum_{i=1}^{N} h_{Average_{No_xi}}}{n}\left(\frac{\$}{kg}\right) \quad (2.26)$$

$$h_{Co_2i} = \frac{\sum_{i=1}^{N} h_{Average_{Co_2i}}}{n}\left(\frac{\$}{kg}\right) \quad (2.27)$$

where h_{SO2i} = Common price penalty factor of SO_2, h_{NOXi} = Common price penalty factor of NO_x, h_{CO2i} = Common price penalty factor of CO_2.

2.7 Constraints

2.7.1 Power balance constraint

At each period of time, total generated electrical power should be equal to load demand.

$$\sum_{i=1}^{N} P_i = P_G = P_D \text{ MW} \quad (2.28)$$

where P_G = Total power generation of the system, P_D =Total demand of the system.

2.7.2 Generator operational constraints

For each generation unit, the generated power should be in a certain bound. The generation capacity constraint is formulated using (2.29)

$$P_{i,\min} \le P_i \le P_{i,\max,}\ where\ i = \overline{1.n} \quad (2.29)$$

where $P_{i,\min}$ =minimum value of the real power allowed at generator i, $P_{i,\max,}$ = maximum real power generation limit of generator i.

III. GRASSHOPPER OPTIMIZATION ALGORITHM (GOA)

Nature with its gradual process of evolution changes the environment continuously. Nature is one of the biggest sources of inspiration and human develops many technical theories by inspiring the nature. The life cycle of grasshopper has inspired the researchers to solve the optimization problem. The grasshopper optimization problem is one such nature inspiring problem and was developed by Seyedali Mirijalili in 2017. CEMED problem is solved by applying GOA and it is implemented in this article. GOA is modeled by mimicking the social behaviour of the grasshopper. The grasshopper swarm regularly both in nymph and adult stage and it searches for is prey. The grasshopper travels and finds its prey by exploring the prey and then exploits the prey finally. The algorithm is designed with the model action of exploring and exploiting behavior of grasshopper. In GOA the convergence speed is focused by using this grasshopper exploration model. GOA is relatively economic to other techniques. GOA equalizes the exploration and exploitation. GOA helps to solves many greatest possible problems in science and industry.

The mathematical expression is follows

$$X_i = S_i + G_i + A_i \quad (3.1)$$

where X_i = Position of the i^{th} grasshopper, G_i = Gravity force, S_i = Social interaction and A_i = Wind advection

The eqn. (3.1) is considering the main three aspects of social interaction, gravitational force outcome and wind advection. The above all aspects are consider only through grasshopper movement. The main aspects is originated from grasshoppers and the social interaction discussed as follows

$$S_i = \sum_{\substack{j=1 \\ j \ne i}}^{N} s\left(d_{ij}\right)\hat{d}_{ij} \quad (3.2)$$

where $\hat{d}_{ij}$ = distance between the i^{th} and j^{th} grasshopper and S = social forces.

The social forces s(r), is computed as follows

$$s(r) = f_i e^{\frac{-r}{l}} - e^{-r} \quad (3.3)$$

where *f* = attraction intensity and *l* = attractive length scale.

One more significant characteristic in swarming behavior is the social attraction which involves attraction and repulsion of grasshopper, when they move together and apart in the searching space. The parameters *l* and *f* modify the comfort zone, attraction region, and repulsion region appreciably.

The function S will explicitly segregate the space between repulsion region, comfort zone and attraction region. This S function returns the values close to zero with distances greater than 10.

The gravity force (G_i), is computed as follows

$$G_i = -g\hat{e}_g \quad (3.4)$$

where g = gravitational constant, $\hat{e}_g$ = unity vector towards the centre of earth.

The wind advection (A_i), is computed as follows

$$A_i = u\hat{e}_w \quad (3.5)$$

where u = constant drift,

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$\hat{e}_w$ = unity vector in the direction of wind.

$$X_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} s\left(\left|x_j - x_i\right|\right)\frac{x_j - x_i}{d_{ij}} - g\hat{e}_g + u\hat{e}_w \qquad (3.6)$$

Mathematically the model cannot be used directly because either the grasshoppers swiftly reach the comfort zone or the swarm does not move towards specified point. Further a modified version of this equation is implied as follows to solve the optimization problem.

$$X_i^d = c\left(\sum_{\substack{j=1 \\ j\neq i}}^{N} c\,\frac{ub_d - lb_d}{2}\, s\left(\left|x_j^d - x_i^d\right|\right)\frac{x_j - x_i}{di_j}\right) + \hat{T}_d \qquad (3.7)$$

where u_{bd} = upper limit in the Dth dimension, l_{bd} = lower limit in the Dth dimension, $s(r) = f_i e^{\frac{-r}{l}} - e^{-r}, \hat{T}_d$ = value of the Dth dimension in the target, c = decreasing coefficient to shrink the comfort zone, repulsion zone and attraction zone.

The coefficient c reduces the comfort zone proportional to the number of iterations and is calculated as follows

$$c = c_{\max} - l\,\frac{c_{\max} - c_{\min}}{L} \qquad (3.8)$$

where c_{max} = coefficient c maximum limit, c_{min} = coefficient c minimum limit, l = current iteration, L = maximum iteration count.

In GOA it is assumed that the fittest grasshopper during optimization is the target. This will assist GOA to save the most promising target at every solution in the search space. This is done with the hope of finding a better and more accurate target as the best outcome. The above discussions make obvious the effectualness of the GOA algorithm in finding the global optimal solution in a given search space.

Steps for grasshopper algorithm

Step 1: To assign the initial population of grasshoppers.

Step 2: Compute the suitability of preliminary stage of grasshoppers.

Step 3: Find the perfect grasshopper in the preliminary population.

Step 4: Grasshopper positions

4.1Grasshoppers change the position in the vast search space.

4.2 To fix the values for all grasshoppers.

4.3 Update the approximate reaching position.

Step 5: Expected solution is reached by maximum iteration.

IV. NUMERICAL SIMULATION RESULTS AND DISCUSSIONS

A simulation study is performed to validate the possibility and effectiveness of the proposed GOA algorithm for the solution of various ED problems through the following five scenarios of six unit multiple emission system.

Scenario A: Fuel Cost Minimization.

Scenario B: Multiple Emissions Dispatch.

Scenario C: Combined Multiple Emissions Dispatch.

Scenario D: Combined Economic Emission Dispatch

Scenario E: Combined Economic Multiple Emissions Dispatch

The data for six unit multiple emission system such as third order fuel cost functions, third order multiple emission coefficients and generator limit values are adapted from [9].The CEMED problem is executed on a Core i5, 2.65GHz PC with 4 GB RAM. The Matlab 7.10 platform is used for the implementation of the proposed GOA code. To achieve the optimal total cost, CEMED problem is examined with six different price penalty factors and their effect on cost minimization process is analyzed to fetch the most optimal 'h' parameter for the scenarios D & E. Further, the performance of GOA is compared with various optimization algorithms.

Scenario A: Fuel Cost Minimization.

In this scenario, the proposed method is applied for fuel cost minimization (2.1) for the 6-unit multiple emission test system for different load demands of 150MW, 175MW, 200MW and 225MW. The pure economic dispatch for cost minimization is carried out and the obtained outcomes are depicted in Table. 1. It is obvious from Table 1, the fuel cost obtained by the proposed GOA method is less than the cost fetched by SA [6], PSO [8] and LAGR [9] in literature. Table 1 also details the individual pollutant emissions during most optimal fuel cost minimization process of GOA.

The variations of fuel cost for 100 iterations are carried out and are illustrated by convergence characteristics as shown in Fig. 1. Fig. 2 shows the variation of fuel cost for four different demands and different algorithms in the literature which clears the superiority of GOA over other algorithms.

Table 1: Comparison of best solutions of fuel cost minimization by different algorithms.

		150 MW	**175 MW**	**200 MW**	**225 MW**
GOA	P1	50.00	50.00	50.00	50.00
	P2	20.00	20.00	20.00	36.53
	P3	15.00	15.00	15.00	15.99
	P4	19.62	29.60	42.25	49.34
	P5	19.48	25.02	32.75	33.14
	P6	25.90	35.38	40.00	40.00
	F_c	2699.03	3168.67	3702.91	4310.53
SA($/h)[6]		2705.21	3220.51	3735.73	4321.51
PSO($/h)[8]		2734.20	3236.30	3784.90	4402.30
LAGR($/h) [9]		2729.34	3475.40	4210.30	5130.53
E_{SO2} (kg/h)		3142.78	3924.20	4802.34	5435.61
E_{NOX}(kg/h)		2368.06	2857.15	3398.43	3898.77
E_{CO2}(kg/h)		2627.77	3227.43	3848.79	4319.97

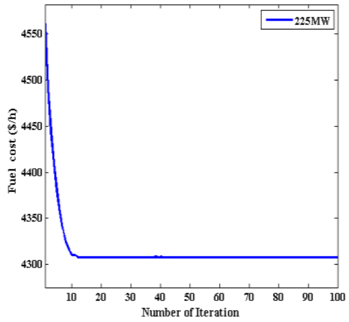

Fig. 1 Convergence characteristics of GOA during fuel cost minimization process

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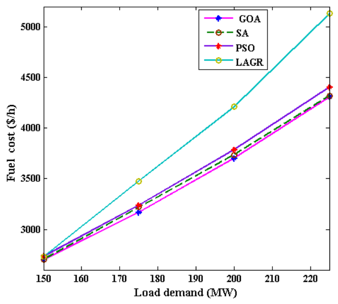

Fig. 2 Comparison of fuel cost by different algorithms for various demands

Scenario B: Multiple Emissions Dispatch.

In this scenario, the Multiple Emissions Dispatch (MED) is carried out on a chosen test system having 6 thermal generators independently by (2.2), (2.3) and (2.4) respectively. The feasibility of the proposed method is tested with 4 different loading conditions. The best SO_2 emission dispatch results obtained by GOA and best compromising results by other algorithms are presented in Table. 2. For a demand of 150 MW, 175MW, 200MW and 225MW, the minimum SO_2 emission obtained is 2745.20 Kg/h, 3257.30 Kg/h, 3907.08 Kg/h and 4619.79 Kg/h respectively, which are much less than the amount of SO_2 emission achieved by other algorithms. During independent SO_2 emission minimization process, the fuel cost achieved for different demands are also tabulated.

Further with the objective of minimizing the NO_x pollutants, the emission minimization process is carried out by (2.3) and the results are listed in Table 3. For a demand of 150MW, 175MW, 200MW and 225MW, the amount of NO_x emission fetched by proposed method is 2202.24 Kg/h, 2580.34 Kg/h, 3016.17 Kg/h and 3499.20 Kg/h respectively, which are lesser than the NO_x emission pollutants fetched by other algorithms. Similarly, the CO_2 pollutants minimization is carried out by the proposed approach and the outcomes are depicted in Table 4 along with the CO_2 emissions identified by other renowned algorithms. The obtained schedule clearly depicts the suitability of GOA for Emission minimization problem. The convergence characteristics of the best emission yielded in 100 iterations by the proposed GOA for SO_2, NO_x and CO_2 emission minimization process is illustrated in Fig. 3, Fig. 5 and Fig. 7 respectively.

Table 2. Comparison of best solutions for E_{SO2} (kg/h) emission minimization by different algorithms

		150 MW	175 MW	200 MW	225 MW
GOA	P1	50.00	50.00	50.00	50.00
	P2	26.82	43.00	48.90	53.23
	P3	41.18	50.00	50.00	50.00
	P4	10.00	10.00	15.33	22.47
	P5	10.00	10.00	18.17	24.55
	P6	12.00	12.00	17.60	24.75
	E_{SO2}(kg/h)	2745.20	3257.30	3907.08	4619.79
SA (kg/h) [6]		3138.44	3763.47	4553.97	5287.30
PSO(kg/h) [8]		3193.60	3904.90	4670.60	5426.10
LAGR(kg/h)[9]		3091.64	4146.17	5053.58	6106.49
F_C($/h)		3079.12	3783.66	4241.41	4722.35

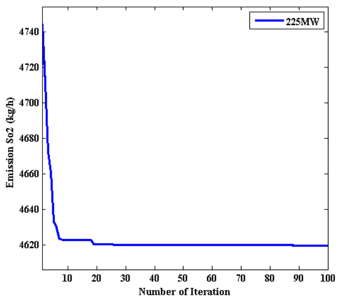

Fig. 3 Convergence characteristics of SO_2emission minimization process

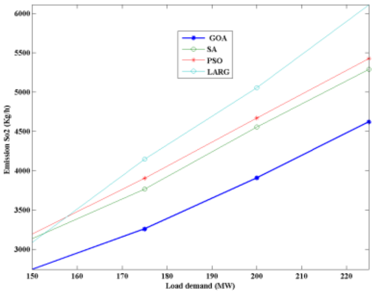

Fig. 4 Comparison of SO_2 emission minimization by different algorithms

Table 3: Comparison of best solutions for E_{NOX} (kg/h) emission minimization by different algorithms

		150 MW	175 MW	200 MW	225 MW
GOA	P1	50.00	50.00	50.00	50.00
	P2	20.00	34.79	44.48	53.38
	P3	15.00	18.21	24.84	29.71
	P4	10.00	10.00	10.00	13.73
	P5	43.00	50.00	50.00	50.00
	P6	12.00	12.00	20.68	28.18
	E_{NOX} (kg/h)	2202.24	2580.34	3016.17	3499.20
SA (kg/h) [6]		2379.50	2789.92	3285.64	3781.19
PSO(kg/h) [8]		2424.60	2879.70	3373.20	3877.60
LAGR(kg/h)[9]		2448.21	2604.88	3102.07	3798.38
F_C($/h)		2855.68	3516.15	4081.51	4652.76

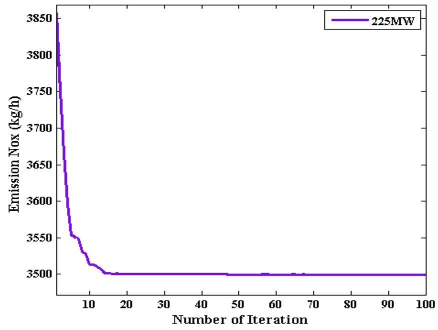

Fig. 5 Convergence characteristics of NO_x emission minimization process

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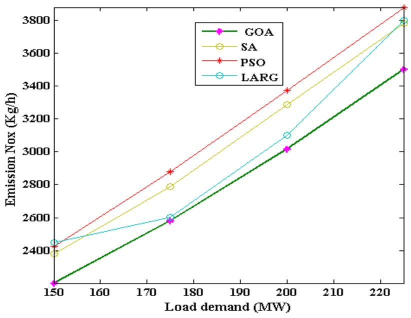

Fig. 6 Comparison of NO_x emission minimization by different algorithms

Table 4: Comparison of best solutions for E_{CO2} (kg/h) emission minimization by different algorithms

		150 MW	175 MW	200 MW	225 MW
GOA	P1	50.00	50.00	50.00	50.00
	P2	28.65	36.53	44.04	49.67
	P3	19.19	26.89	34.14	40.10
	P4	30.16	39.58	48.25	50.00
	P5	10.00	10.00	11.57	20.04
	P6	12.00	12.00	12.00	15.19
	E_{CO2}(kg/h)	2415.11	2880.27	3416.01	4019.53
SA(kg/h) [6]		2568.94	3094.68	3714.33	4324.30
PSO (kg/h) [8]		2607.10	3178.00	3771.50	4403.00
LAGR(kg/h) [9]		2537.12	3613.53	4473.36	5502.52
F_C($/h)		2838.99	3446.23	4079.48	4645.63

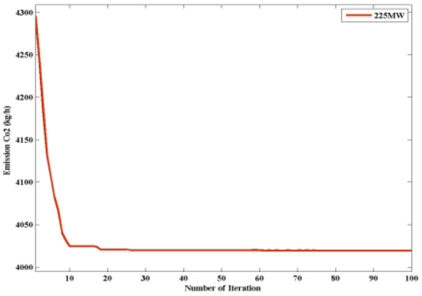

Fig. 7 Convergence characteristics of CO_2emission minimization process

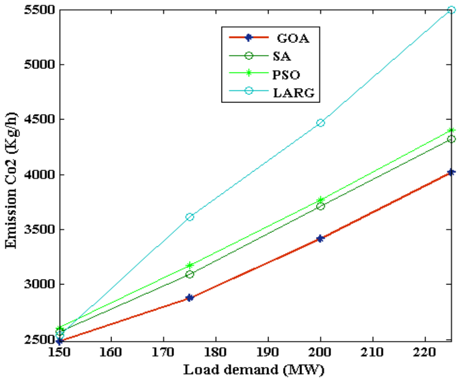

Fig. 8 Comparison of CO_2 emission minimization by different algorithms

Scenario C: Combined Multiple Emissions Minimization.

This scenario details the combined multiple emission minimization process to demonstrate how well the proposed approach works. In this scenario, the performance of proposed method is analyzed by carrying out Combined multiple emissions minimization (2.5) by combining all the emission pollutants SO_2, NO_x and CO_2. Table 5 present the pure emission numerical results. This analysis is first of its class in literature and hence no comparison can be made for this combined multiple emissions minimization problem considering cubic emission functions. Moreover, the convergence characteristic for pure emission optimization is available in Fig. 9 which proves the efficient performance of GOA in achieving better solutions. Table 5 also details the fuel cost obtained during the combined multiple emissions minimization problem.

Table 5: Combined multiple emissions dispatch solutions for different power demands

		150 MW	175 MW	200 MW	225 MW
GOA	P1	50.00	50.00	50.00	50.00
	P2	36.21	41.15	46.24	50.76
	P3	31.79	36.11	40.56	44.51
	P4	10.00	16.49	23.18	28.66
	P5	10.00	19.25	25.30	30.36
	P6	12.00	12.00	14.72	20.71
	E_{SO2}(kg/h)	2784.74	3364.98	4003.51	4691.63
	E_{NOx}(kg/h)	2367.41	2784.26	3239.87	3721.53
	E_{CO2} (kg/h)	2492.52	3002.42	3556.76	4167.01
	E_T(kg/h)	7644.67	9151.66	10800.14	12580.16
	F_c($/h)	3000.12	3531.48	4078.91	4637.92

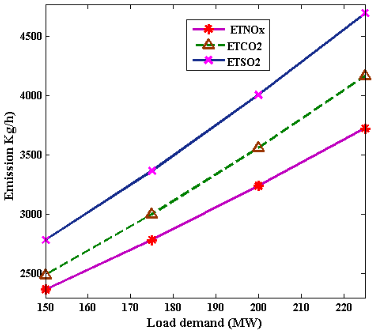

Fig. 9 Variance of SO2. NO_X and CO_2 emissions for various load demand

Scenario D: Combined Economic Emission Dispatch

This scenario analyzes the performance of proposed method in order to solve Combined Economic Emission Dispatch (CEED) considering the pollutant emissions individually. To blend the two conflicting objectives of cost and emission into a single objective function, a price penalty factor is being used in this scenario. In order to handle this problem, six different types of penalty factors $h_{min-max}$, $h_{min-min}$, $h_{max-max}$, $h_{max-min}$, $h_{average}$ and h_{common} are used. Eq. (2.6), (2.7) and (2.8) are considered as objective functions. The numerical results of Economic SO_2 Emission Dispatch (E_{SO2}ED) (2.6), Economic NO_x Emission Dispatch (E_{NOX}ED) (2.7) and Economic CO_2 Emission Dispatch (E_{CO2}ED) (2.8) considering 6 different penalty factors for four different power demands are presented in Table 6, Table 7 and Table 8 respectively. The dispatch results shows the variation of real power output of each generating units, fuel cost, emission of E_{SO2}, E_{NOX}, E_{CO2} and their corresponding total cost as the penalty factor changes.

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Table 6: $E_{SO2}ED$ considering various price penalty factors

Price penalty factor	P_D (MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	F_C ($/h)	E_{SO2} (kg/h)	F_{TSO2} ($/h)
$h_{min-max}$	150	50.00	20.00	15.00	24.49	22.89	17.62	2711.70	3143.05	3073.71
$h_{max-max}$		50.00	20.00	15.00	29.16	23.84	12.00	2734.36	3170.69	5500.87
$h_{max-min}$		50.00	20.00	15.00	14.08	10.92	40.00	2737.26	3158.44	27610.12
$h_{min-min}$		50.00	20.00	15.00	22.48	24.79	17.73	2736.75	3164.94	5445.52
$h_{average}$		50.00	20.00	15.00	15.34	14.08	35.58	2717.72	3203.49	10086.98
h_{common}		50.00	20.00	15.00	28.01	24.99	12.00	2734.34	3167.56	3256.21
$h_{min-max}$	175	50.00	20.00	15.00	34.58	28.76	26.66	3184.10	3916.87	3640.65
$h_{max-max}$		50.00	20.56	15.00	31.36	25.48	32.60	3172.05	3907.77	6400.13
$h_{max-min}$		50.00	20.00	15.00	27.17	22.83	40.00	3173.16	3953.56	29695.43
$h_{min-min}$		50.00	20.00	15.00	31.86	31.60	26.54	3188.68	3910.25	6413.01
$h_{average}$		50.00	20.00	15.00	26.70	23.30	40.00	3173.04	3953.17	11578.69
h_{common}		50.00	20.00	15.00	29.81	26.10	34.09	3169.15	3917.71	3814.61
$h_{min-max}$	200	50.00	20.00	15.00	44.93	34.65	35.42	3717.06	4805.11	4281.20
$h_{max-max}$		50.00	28.71	15.00	30.21	37.71	38.37	3717.12	4630.19	7458.52
$h_{max-min}$		50.00	28.02	15.00	35.38	31.60	40.00	3715.53	4640.08	34011.03
$h_{min-min}$		50.00	20.00	15.00	41.25	38.64	35.11	3727.30	4786.07	7525.53
$h_{average}$		50.00	25.10	15.00	37.09	32.81	40.00	3708.90	4691.17	13344.54
h_{common}		50.00	28.89	15.00	36.19	30.02	39.90	3716.30	4630.08	4479.13
$h_{min-max}$	225	50.00	31.68	15.00	50.00	38.54	39.78	4309.67	5536.21	4983.33
$h_{max-max}$		50.00	37.98	15.00	45.76	36.26	40.00	4311.34	5406.78	8622.02
$h_{max-min}$		50.00	35.58	15.00	45.07	39.35	40.00	4314.59	5437.14	38933.28
$h_{min-min}$		50.00	23.15	15.00	50.00	46.85	40.00	4348.28	5711.05	8795.27
$h_{average}$		50.00	33.63	15.00	46.51	39.86	40.00	4313.80	5476.59	15358.51
h_{common}		50.00	37.82	22.70	41.23	33.25	40.00	4329.89	5218.52	5189.68

Table 7: $E_{NOX}ED$ considering various price penalty factors.

Price penalty factor	P_D (MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	F_C ($/h)	E_{NOX} (kg/h)	F_{TNOX} ($/h)
$h_{min-max}$	150	50.00	20.00	15.00	25.67	22.91	16.42	2715.53	2365.97	3069.67
$h_{max-max}$		50.00	20.00	15.00	27.91	10.00	27.09	2723.50	2347.53	5282.40
$h_{max-min}$		50.00	20.00	26.46	10.00	10.00	33.54	2838.57	2433.02	27334.70
$h_{min-min}$		50.00	20.00	20.63	32.35	10.00	17.02	2791.24	2502.66	5857.23
$h_{average}$		50.00	22.79	43.07	10.00	10.00	14.14	3075.80	2764.88	210256.57
h_{common}		50.00	20.00	15.00	15.03	26.06	23.91	2710.67	2304.24	3649.72
$h_{min-max}$	175	50.00	20.00	15.00	35.58	28.74	25.68	3187.55	2851.10	3647.33
$h_{max-max}$		50.00	20.00	15.00	33.84	23.44	32.72	3195.24	2817.77	6277.72
$h_{max-min}$		50.00	31.93	33.07	10.00	10.00	40.00	3450.49	2896.02	31481.45
$h_{min-min}$		50.00	28.44	26.06	37.68	10.00	22.82	3350.27	2974.10	7192.12
$h_{average}$		50.00	29.82	50.00	13.50	10.00	21.68	3656.04	3324.75	212337.18
h_{common}		50.00	20.00	15.00	24.62	32.29	33.09	3190.26	2777.19	4322.06
$h_{min-max}$	200	50.00	20.00	15.00	45.84	34.63	34.53	3720.59	3404.92	4297.88
$h_{max-max}$		50.00	26.26	15.00	40.71	29.00	39.03	3724.50	3377.68	7404.78
$h_{max-min}$		50.00	42.74	40.18	17.08	10.00	40.00	4061.19	3386.75	36151.36
$h_{min-min}$		51.95	36.70	30.88	42.67	10.00	27.80	3955.80	3508.93	8622.64
$h_{average}$		50.00	37.49	50.00	22.48	10.00	30.03	4150.92	3991.15	214653.46
h_{common}		50.00	28.04	15.00	31.16	36.59	39.21	3732.40	3241.26	5053.32
$h_{min-max}$	225	50.00	31.54	15.00	50.00	38.48	39.98	4309.91	3889.35	5015.09
$h_{max-max}$		50.00	35.29	20.18	46.59	32.94	40.00	4317.30	3854.56	8617.93
$h_{max-min}$		50.00	54.55	45.36	25.09	10.00	40.00	4697.02	3925.69	41345.99
$h_{min-min}$		56.15	44.00	35.29	47.27	10.00	32.29	4609.76	4114.06	10146.22
$h_{average}$		50.00	37.84	45.33	50.00	31.83	10.00	4689.97	4749.67	217274.68
h_{common}		50.00	39.71	17.90	37.05	40.34	40.00	4340.27	3702.57	5849.18

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Table 8: $E_{CO2}ED$ considering various price penalty factors.

Price penalty factor	P_D (MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	F_C ($/h)	E_{CO2} (kg/h)	F_{TCO2} ($/h)
$h_{min-max}$	150	50.00	20.00	15.00	25.31	23.37	16.32	2715.94	2556.91	3027.57
$h_{max-max}$		50.00	20.00	15.00	23.30	19.64	22.06	2734.42	2524.04	4981.61
$h_{max-min}$		50.00	20.00	15.00	17.24	10.00	37.76	2733.03	2739.25	26823.12
$h_{min-min}$		50.00	20.00	15.00	29.11	23.89	12.00	2734.34	2525.89	5495.30
$h_{average}$		50.00	20.00	15.00	30.59	10.00	24.41	2729.51	2538.98	9270.73
h_{common}		50.00	20.00	15.00	25.89	18.13	20.98	2737.09	2504.51	3324.79
$h_{min-max}$	175	50.00	20.00	15.00	35.34	29.06	25.60	3187.97	3143.14	3599.55
$h_{max-max}$		50.00	20.00	15.00	32.78	26.08	31.14	3172.36	3177.15	5914.56
$h_{max-min}$		50.00	20.00	15.00	33.90	16.10	40.00	3190.02	3232.51	30754.95
$h_{min-min}$		50.00	20.00	15.00	40.39	31.67	17.94	3228.98	3108.36	6573.20
$h_{average}$		50.00	20.00	15.00	41.16	13.86	34.98	3209.99	3149.50	10496.25
h_{common}		50.00	20.00	15.00	35.80	24.05	30.15	3176.85	3146.76	3915.26
$h_{min-max}$	200	50.00	20.00	15.00	45.57	34.77	34.66	3720.13	3802.65	4243.96
$h_{max-max}$		50.00	27.84	15.00	39.20	30.52	37.44	3721.12	3761.79	6997.19
$h_{max-min}$		50.00	20.00	19.87	44.28	25.85	40.00	3726.52	3771.65	35449.78
$h_{min-min}$		50.00	20.00	15.00	49.51	38.03	27.46	3762.99	3775.95	7794.73
$h_{average}$		50.00	20.00	15.00	49.98	25.02	40.00	3720.64	3794.61	11894.12
h_{common}		50.00	20.00	15.00	49.48	38.03	27.49	3762.82	3776.14	7794.73
$h_{min-max}$	225	50.00	31.58	15.00	50.00	38.42	40.00	4309.55	4395.24	4950.37
$h_{max-max}$		50.00	36.90	15.57	47.05	35.48	40.00	4310.77	4336.89	8160.80
$h_{max-min}$		50.00	26.49	26.77	50.00	31.74	40.00	4332.66	4312.29	40750.75
$h_{min-min}$		50.73	20.00	17.39	50.00	47.00	39.88	4360.06	4584.37	9218.28
$h_{average}$		50.00	31.25	15.00	50.00	38.82	39.93	4310.72	4402.73	13698.53
h_{common}		50.00	36.49	18.13	48.89	31.49	40.00	4315.70	4293.86	5323.29

Table 9: Various Price penalty factor impacts on $E_{SO2}ED$, $E_{NOX}ED$ and $E_{CO2}ED$ problem for P_D=225MW.

Pollutant	ED Solution	Min - Max	Max - Max	Max - Min	Min – Min	Average	Common
SO_2	F_C ($/h)	100%	100.04%	100.11%	100.89%	100.09%	100.47%
	E_{SO2}(kg/h)	100%	97.66%	98.21%	103.16%	98.92%	94.26%
	F_{TSO2} ($/h)	100%	173.01%	781.25%	176.49%	308.19%	104.14%
NO_X	F_C ($/h)	100%	100.17%	108.98%	106.96%	108.82%	100.7%
	E_{NOX}(kg/h)	100%	99.10%	100.93%	105.78%	122.12%	95.19%
	F_{TNOX} ($/h)	100%	171.84%	824.43%	202.31%	4332.41%	116.63%
CO_2	F_C ($/h)	100%	100.03%	100.68%	101.16%	100.01%	100.13%
	E_{CO2}(kg/h)	100%	98.67%	98.11%	104.30%	100.17%	97.68%
	F_{TCO2} ($/h)	100%	164.85%	823.17%	186.21%	276.72%	107.53%

In addition, Table 9 outlines the percentage comparison of dispatch values keeping the values obtained considering $h_{min-max}$ as base value. In this table, it is aimed to outline the results deviation subsequent to elaborating various penalty factors. The percentage results are computed from associated ED solutions represented in Table 6, 7 and 8. Table 9 shows how much the dispatch results deviate from their associated optimal values for a demand of 225 MW.

In $E_{SO2}ED$ the total cost obtained using min-max penalty factor is 4950.37 $/h which is much less than the cost found using rest of the penalty factors. The cost achieved by other penalty factors such as max-max, max-min, min-min, average and common are 164.85%, 823.175%, 186.21%, 276.72% and 107.53% respectively more than the cost found using min-max penalty factor. Similarly, for $E_{NOX}ED$ and $E_{CO2}ED$, the total cost fetched by min-max penalty factor is much less than cost found by other penalty factors. As it can be seen from Table 9, the cost computed by conceiving $h_{min-max}$ penalty factor is suitably minimal when compared to the cost obtained by all other price penalty factors.

Scenario E: Combined Economic Multiple Emissions Dispatch.

This scenario investigates the combined impact of SO_2, NO_X and CO_2 pollutants on ED problem, by carrying out the Combined Economic Multiple Emission Dispatch by Eq. (2.9) considering all 3 pollutants jointly at the same power demand. As discussed in scenario D, various price penalty factors are considered for blending the conflicting objectives of SO_2, NO_X and CO_2 emission and fuel cost and the CEMED is carried out. Table 10 present the numerical results of CEMED obtained using six different penalty factors for four load demands.

Table 10: CEMED results considering various price penalty factors

Price penalty factor	P_D (MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	F_C ($/h)	E_{SO2} (kg/h)	E_{NOX} (kg/h)	E_{CO2} (kg/h)	E_T (kg/h)	F_T ($/h)
$h_{min-max}$	150	50.00	20.00	15.00	27.61	25.39	12.00	2734.53	3166.76	2364.04	2541.14	8071.94	3717.68
$h_{max-max}$		50.00	20.00	15.00	25.27	17.30	22.43	704.87	3146.74	2406.18	2564.50	8117.42	10254.98
$h_{max-min}$		50.00	27.01	20.73	30.26	10.00	12.00	2842.29	3025.40	2469.08	2415.85	7910.33	79742.74
$h_{min-min}$		50.00	20.00	15.00	38.18	10.00	16.82	2764.49	3242.75	2564.28	2473.41	8280.44	11516.94
$h_{average}$		50.00	20.00	15.00	37.35	10.00	17.65	2726.79	3215.20	2473.15	2699.72	8388.07	25433.10
h_{common}		50.00	29.16	20.60	16.34	20.56	13.34	2703.50	3137.09	2354.20	2592.26	8083.55	4600.38
$h_{min-max}$	175	50.00	20.00	15.00	40.93	33.93	15.14	3250.72	3993.69	2870.84	3117.24	9981.77	4474.60
$h_{max-max}$		50.00	23.77	15.00	32.65	23.92	29.66	3188.08	3859.37	2854.08	3129.07	9842.52	12241.41
$h_{max-min}$		50.00	26.82	20.78	27.40	10.00	40.00	3279.69	3806.94	2953.04	3184.37	9944.35	87164.46
$h_{min-min}$		52.23	20.00	15.00	49.04	10.00	28.73	3291.09	4120.81	3193.59	3114.64	10429.04	14283.26
$h_{average}$		50.00	25.44	16.12	33.44	10.00	40.00	3245.08	3926.44	3006.93	3186.74	10120.11	29789.51
h_{common}		50.00	28.64	16.74	27.46	25.81	26.35	3224.04	3745.57	2780.32	3101.86	9627.75	5483.28
$h_{min-max}$	200	50.00	22.85	15.00	49.48	39.42	23.25	3792.84	4822.04	3394.32	3746.15	11962.51	5337.45
$h_{max-max}$		50.00	31.04	15.00	38.82	29.48	35.66	3727.40	4592.46	3325.31	3715.56	11633.33	14413.52
$h_{max-min}$		50.00	33.90	29.05	37.05	10.00	40.00	3882.99	4386.78	3467.04	3643.16	11496.98	101015.22
$h_{min-min}$		50.00	33.2	27.32	39.48	10.00	40.00	4623.86	5445.33	4341.81	4439.51	14226.65	20835.55
$h_{average}$		50.00	32.59	26.88	40.53	10.00	40.00	3865.33	4461.16	3501.81	3642.95	11605.92	34850.66
h_{common}		50.00	35.58	22.44	32.13	29.09	30.76	3791.25	4352.96	3231.12	3635.97	11220.05	6424.13
$h_{min-max}$	225	53.48	33.23	15.00	50.00	44.09	29.20	4407.67	5527.44	3868.42	4403.87	13799.73	6282.70
$h_{max-max}$		50.00	37.66	17.83	44.72	34.79	40.00	4315.15	5338.42	3819.56	4322.26	13480.24	16783.68
$h_{max-min}$		50.00	42.57	35.94	46.49	10.00	40.00	4527.06	5063.32	4043.06	4169.15	13275.53	116822.70
$h_{min-min}$		65.10	35.06	24.86	50.00	10.00	39.98	4625.18	5475.46	4350.66	4453.94	14280.05	20834.42
$h_{average}$		50.00	41.99	33.17	49.84	10.00	40.00	4509.93	5153.06	4080.40	4168.95	13402.42	40574.99
h_{common}		50.00	42.28	28.00	36.96	32.49	35.27	4385.38	5019.42	3716.96	4218.24	12954.62	7425.30

Table 11: Various Price penalty factor impacts on CEMED problem for P_D=225MW.

ED Solution	$h_{min-max}$	$h_{max-max}$	$h_{max-min}$	$h_{min-min}$	$h_{average}$	h_{common}
Fuel cost ($/h)	100%	97.90%	102.27%	104.93%	102.32%	99.49%
E_{SO2}(kg/h)	100%	96.58%	91.60%	99.05%	93.22%	90.80%
E_{NOX}(kg/h)	100%	98.73%	104.51%	112.46%	105.47%	96.08%
E_{CO2}(kg/h)	100%	98.14%	94.67%	101.13%	94.66%	95.78%
E_T(kg/h)	100%	97.68%	96.20%	103.48%	97.12%	93.87%
$F_{T\text{-}SO2\text{-}NOx\text{-}CO2}$ ($/h)	100%	267.14%	1859.43%	331.61%	645.82%	118.18%

Table 11 outline the results deviation by other penalty factors in comparison to results using min-max penalty factor as base value of 100%. As per Table 11, the system total cost computed using the min-max penalty factor is least in comparison with other penalty factors. Furthermore Table 11 details the variation of solutions of Fuel cost, E_{SO2}, E_{NOX}, ET_{CO2} and total emission while considering other penalty factors during CEMED and it exhibits the minimum value.

The comparative results for pure CEMED problem is reported in Table 12 for four different power demands. For a demand of P_D = 150 MW considering min-max penalty factor, the total cost obtained is 3717.68 $/h which is much less than the cost achieved by Modified biogeography based optimization algorithm MBO [5], Simulated Annealing (SA) [6], [7], Particle Swarm Optimization (PSO) [8], Lagrange's method (LAGR) [9] in the literature. Similarly for other demands of 175MW, 200MW and 225MW CEMED is carried and the simulation results depict that the proposed approach has very minimum total cost when compared to other existing algorithms and methods.

Table 12: Comparison of CEMED results obtained by different algorithms

	$h_{min-max}$	$h_{max-max}$	$h_{max-min}$	$h_{min-min}$	$h_{average}$	h_{common}
P_D=150MW						
GOA	**3717.68**	10254.98	79742.74	11516.94	25433.11	4600.38
MBO [5]	-	10255.21	-	-	-	-
SA [6, 7]	3718.21	10261.49	-	-	7043.58	-
PSO [8]	-	10385.00	-	-	-	-
LAGR [9]	3768.28	10264.56	-	-	7500.75	8122.63
P_D=175MW						
GOA	**4474.60**	12241.41	87164.46	14283.26	29789.51	5483.28
MBO [5]	-	12241.67	-	-	-	-
SA [6,7]	4474.78	12280.04	-	-	8417.25	-
PSO [8]	-	12425.00	-	-	-	-
LAGR [9]	4551.67	13251.51	-	-	8987.32	9802.29

P_D=200MW						
GOA	**5337.45**	14413.52	101015.22	20835.55	34850.66	6424.13
MBO [5]	-	14413.71	-	-	-	-
SA [6,7]	5337.56	14421.30	-	-	9923.07	-
PSO [8]	-	14642.00	-	-	-	-
LAGR [9]	5438.00	16077.40	-	-	11623.52	10137.40
P_D=225MW						
GOA	**6282.70**	16783.68	116885.42	20832.22	40575.48	7425.30
MBO [5]	-	16784.34	-	-	-	-
SA [6,7]	6283.04	16790.69	-	-	11570.32	-
PSO [8]	6418.90	17125.00	-	-	12583.00	-
LAGR [9]	6418.90	19661.32	-	-	13283.85	14936.26

V. CONCLUSION

In this paper, GOA algorithm is proposed and successfully implemented to solve the combined economic and multiple emission dispatch problem. The CEMED problem is solved considering six different price penalty factors. The proposed approached has been employed to six-unit system with multiple emissions expressed as cubic cost functions. Five different scenarios and constraints are used to demonstrate the feasibility of proposed method and the following conclusions are observed.

1. In CEED and CEMED problem, among the six different price penalty factors, **Min-Max** penalty factor appears to be more competitive in fetching minimum **total cost ($F_{T-SO2-NOx-CO2}$)** in the chosen test system.
2. Further during CEMED optimization process, the minimum **fuel cost (F_C)** is achieved while considering **Max-Max** penalty factor and minimum **total emission** (**E_T**) is obtained when choosing **Common** penalty factor.

From the test instances, it was observed that the novel GOA outperforms MBO, SA, PSO and LAGR in most of the test instances with significant values in ED, MED, CEED and CEMED. Therefore, it may be finally concluded that the proposed GOA methodology appears to be reliable optimization algorithm for solution of different multi-objective power system optimization problems.

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AUTHORS PROFILE

R. Karthikeyan is currently Lecturer (Assistant professor on deputation from Annamalai University), Department of EEE, Alagappa government polytechnic college, Karaikudi, Tamilnadu. He has been teaching Diploma, UG & PG classes well over 11 years. His research interests include power system operations and control.

Dr. S. Subramanian is currently professor, Department of EEE at Annamalai University, Chidambaram, Tamilnadu. He has been teaching UG & PG classes well over two decades. He has to his credit more than 125 research articles of which most of the papers are SCI/Scopus Indexed. He is a senior member in IEEE, ISTE and IOE.

Dr. E. B. Elanchezhian is currently Lecturer (Assistant professor on deputation from Annamalai University), Department of EEE, Government polytechnic college, Srirangam, Tamilnadu. He has done Ph.D at Annamalai University in 2016. He has been teaching Diploma, UG & PG classes well over 12 years. He has to his credit 19 research papers of which 6 papers are SCI/Scopus Indexed. He is a senior member in IEEE, ISTE & IOE.