Combined Economic Emission Dispatch using Novel Bat Algorithm

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July 17, 2018

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***Abstract*— Electricity generation is mainly from thermal power plants, which also contribute to environmental pollutants, like SO_2 (Sulphur dioxide), CO_2 (Carbon dioxide), and NO_x (Oxides of Nitrogen). This has made the study of Economic Emission Dispatch (EED) an important research area. This paper introduces Novel Bat Algorithm (NBA) to be applied for solving EED problem using max/max penalty factor. As a test system, a 6 generator bus having cubic cost function is considered. Simulations are performed for individual pollutant analysis, and for combined pollutant analysis, considering different load demands. The results show that NBA performs better when compared with other algorithms available in literature. Convergence graphs are also presented.**

Keywords— Combined Economic Emission dispatch; Novel Bat Algorithm; Cubic cost functions; Pollutant Analysis

I. INTRODUCTION

The increase in population and the dependency on electrically driven machines has led to the need of increasing the electrical energy output. However, the use of renewable energy alone cannot prove satisfactory to meet the energy demand. The conventional energy sources like thermal power plants are hence indispensable in fulfilling the energy needs.

The role of Economic Dispatch (ED) thus becomes significant to minimize the generator fuel cost especially in thermal (coal, fuel oil or natural gas) driven power plants [1]. The issue with the thermal power plants is the emission of pollutants involved. The pollutants harm the environment which indirectly affects the life on Earth. Major pollutants include SO_2, NO_x and CO_2 [2]. The need to optimize the emission rate also plays a major role in ED problem. Such a case, wherein the optimization of a system has a fuel source, emission rate and the generator fuel cost is termed as the Combined Economic Emission Dispatch (CEED) [3].

The CEED problem can be formulated in terms of the objective function having quadratic cost functions and/or cubic cost functions [4]. This work is based on cubic cost functions. Similarly, any ED problem is performed for a time horizon of either one hour, or more than one hour. The former case, when performed for CEED, is termed as Static Combined Economic Emission Dispatch (SCEED) [5], and it is performed in this paper.

Past research has been conducted in CEED considering effect of individual pollutants using Particle Swarm Optimization (PSO) [6] and Simulated Annealing (SA) algorithm [2]. This work uses Novel Bat Algorithm (NBA) to solve the CEED problem with cubic cost functions.

Yang proposed BA in [7] and has seen plenty of modifications since it were proposed [8-12]. The Binary bat algorithm [8] is a variation of bat algorithm which describes the algorithm in terms of discrete binary spaces, instead of the continuous binary spaces. The Novel Complex valued bat algorithm [9] is based on considering the two dimensional properties of the complex number, the real and imaginary parts, which are updated separately. As given in [10], when the bat algorithm is hybridized using the different differential evolution strategies, it is called Hybrid bat algorithm. Using different variations of chaotic maps, the Chaotic bat algorithm [11] was developed. Another modification, the NBA, was proposed in [12] and it shows promising results in case of ED with losses and valve point loading effect [13]. Hence, it is used in this paper, as a first attempt to solve CEED with cubic cost functions and to study its convergence characteristics. A brief review of various other types of bat algorithm has been mentioned in [14], along with the applications they have been used for.

This paper has been arranged as follows: Section 2 describes the mathematical formulation of the CEED problem, while Section 3 describes the Novel Bat Algorithm. The next section presents the data for the test systems and the simulation results, along with the convergence curves. Finally, the paper is concluded outlining the future work that can be performed in this domain.

II. ECONOMIC EMISSION DISPATCH PROBLEM FORMULATION

This section describes the mathematical formulation of the CEED problem, discussing the fuel cost function model, followed by the gas emission model and the price penalty function.

A. Fuel cost function model

The EED problem is a bi-objective function, having a fuel cost equation and an emission objective equation. The fuel cost function can be represented in terms of a cubic fuel cost equation [15] as given in Eq. (1), which is termed as the fuel cost, and having two constraints, the equality constraint (power balance equation) – given in Eq. (2) – and the inequality constraint, shown in Eq. (3).

$$\mathrm{F_{cost(i)}} = \sum_{\mathrm{i=1}}^{\mathrm{n}} a_i \mathrm{P_i^3} + b_i \mathrm{P_i^2} + c_i P_i + \delta_i \quad (1)$$

$$\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{P_i} = \mathrm{P_d} + \mathrm{P_l} \quad (2)$$

$$\mathrm{P_i^{min}} \leq \mathrm{P_i} \leq \mathrm{P_i^{max}} \quad (3)$$

The power loss equation is given by Eq. (4)

$$P_l = \sum_{i=1}^{N} \sum_{j=1}^{N} B_{ij} P_i P_j \quad (4)$$

However, in this paper only lossless case is considered.

B. Gas Emission model

The minimization of pollutant emission is considered as the objective function in case of Emission Dispatch. It is also represented in terms of a cubic equation given in Eq. (5) for SO_2, Eq. (6) for NO_x and Eq. (7) for CO_2.

$$E_{SO_2(i)} = \sum_{i=1}^{n} d_{SO_2(i)} P_i^3 + e_{SO_2(i)} P_i^2 + f_{SO_2(i)} P_i + \gamma_{SO_2(i)} \quad (5)$$

$$E_{NO_x(i)} = \sum_{i=1}^{n} d_{NO_x(i)} P_i^3 + e_{NO_x(i)} P_i^2 + f_{NO_x(i)} P_i + \gamma_{NO_x(i)} \quad (6)$$

$$E_{CO_2(i)} = \sum_{i=1}^{n} d_{CO_2(i)} P_i^3 + e_{CO_2(i)} P_i^2 + f_{CO_2(i)} P_i + \gamma_{CO_2(i)} \quad (7)$$

The objective functions of Emission dispatch of all the three gases can be combined with the fuel cost function to convert the multi-objective function into the single objective function.

C. Price Penalty Factor

For converting the multi-objective function into a single objective function, Eq. (1) and [Eqs. (5)-(7)] are integrated using the price penalty factor, hi. The value of hi is dependent on the equation of pollutant associated with it. Thus, the combined objective function is represented as given in Eq. (8).

$$F(P_i) = F_{cost(i)}(P_i) + h_{SO_{2(i)}} E_{SO_2(i)}(P_i) + h_{NO_x(i)} E_{NO_x(i)} + h_{CO_{2(i)}} E_{CO_2(i)} \quad (8)$$

The term 'h_{SO2}', 'h_{NOx}' and 'h_{CO2}' are the price penalty factors for SO_2, NO_x and CO_2 respectively. The steps involved in the calculation of price penalty factor for a particular load demand [3] are:

A. Ratio between maximum fuel cost and maximum emission of each generator is calculated.

B. Values of price penalty factor are arranged in ascending order.

C. Maximum capacity of each unit P_{max} is added one at a time, starting from the smallest hi, until $P_{max} > P_d$.

D. At this point, hi which is associated with the last unit by following this process is the approximate price penalty factor value for the given load.

Mathematically, it is represented as given in [Eqs. (9) – (11)].

$$h_{SO_2(i)} = \frac{F_{cost(i)}(P_i^{max})}{E_{SO_{2(i)}}(P_i^{max})} \quad (9)$$

$$h_{NO_x(i)} = \frac{F_{cost(i)}(P_i^{max})}{E_{NO_{x(i)}}(P_i^{max})} \quad (10)$$

$$h_{CO_2(i)} = \frac{F_{cost(i)}(P_i^{max})}{E_{CO_{2(i)}}(P_i^{max})} \quad (11)$$

Only max/max price penalty factor method is used in this paper.

III. NOVEL BAT ALGORITHM

Bats are the only mammals with wings and they also have advanced capability of echolocation. Most of the bats use echolocation to a certain degree; among all the species, micro-bats are famous for their extensive use of echolocation, while mega bats do not use them. Micro-bats use echolocation to detect prey, avoid obstacles, and locate their roosting crevices in the dark [7].

If some of the echolocation characteristics of micro-bats are idealized, various bat inspired algorithms can be developed. For simplicity, the following approximate rules are used:

1. All bats use echolocation to sense distance. They also know the difference between food/prey and other background barriers.

2. Bats fly randomly with velocity v_i at position x_i with a fixed frequency f_{min} (or wavelength λ), varying wavelength λ (or frequency f) and loudness A_o to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission (in the range of 0 to 1) depending on the proximity of their targets.

3. Although the loudness can vary in many ways, it is assumed that the loudness varies from a large value A_o to a minimum value A_{min}.

The mathematical equations that can be formulated from the above discussion are given below [12]:

$$\text{rand}(0,1) < A_i \&\& f((x_i) < f(x)) \quad (12)$$

$$f(x) = f(x_i) \quad (13)$$

$$A_i^{t+1} = \nu A_i^t \quad (14)$$

$$r_i^{t+1} = r_i^0 (1 - e^{-\varphi t}) \quad (15)$$

Another simplification is that ray tracing is not used in estimating the time delay. In addition to these simplified assumptions, subsequent approximations have been used for simplicity. Generally, the frequency f in a range [f_{min}, f_{max}] corresponds to a range of wavelengths [λ_{min}, λ_{max}].

In the Bat Algorithm (BA), the Doppler Effect and the idea of foraging of bats was not taken into consideration. In the original BA, each virtual bat is represented by its velocity and position, searches its prey in a D-dimensional space, and its trajectory is obtained. Also according to BA, it is considered that the virtual bats would forage only in one habitat. However, in reality, this is not always the case. In NBA [12], Doppler Effect has been included in the algorithm. Each virtual bat in the proposed algorithm can also adaptively compensate for the Doppler Effect in echoes.

Meanwhile, the virtual bats are considered to have diverse foraging habitats in the NBA. Due to the mechanical behavior of the virtual bats considered in the BA, they search for their food only in one habitat. However, the bats in NBA can search for food in diverse habitats. In summary, the NBA consists of the following idealized rules for mathematical formulation purposes.

1. All bats can move around in different habitats.

2. All bats can compensate for Doppler Effect in echoes.

3. They can adapt and adjust their compensation rate depending upon the proximity of their targets.

The simulation for economic emission dispatch problem with cubic cost functions has been conducted on the standard IEEE 30 bus system using this method and has been found to be most optimal when compared with other methods.

A. Quantum Behavior of Bats

It is assumed that the bats will behave in such a manner that as soon as one bat finds food in the habitat, other bats would immediately start feeding from them. Such an assumption leads to the mathematical formulation of the virtual bat positions as shown below [12]:

$$x_{i,j}^{t+1} = \begin{cases} g_j^t + \theta * \left|mean_j^t - x_{i,j}^t\right| * ln\left(\frac{1}{u_{i,j}}\right), if\ rand_j(0,1) < 0.5, \\ g_j^t - \theta * \left|mean_j^t - x_{i,j}^t\right| * ln\left(\frac{1}{u_{i,j}}\right), if\ rand_j(0,1) < 0.5, \end{cases} \quad (16)$$

B. Mechanical Behavior of Bats

The speed of sound in air is 340 m/s. This speed cannot be exceeded by the bats. Also the Doppler Effect is compensated by the bats and this compensation rate has been mathematically represented as CR. It varies among different bats. A value ξ is considered as the smallest constant in the computer to avoid the possibility of division by zero. The value of CR ∈ [0,1] and the inertia weight $w \in [0,1]$.

Here, if the bats do not compensate for the Doppler Effect at all, then CR is assigned 0, if they compensate fully, CR is assigned 1. Now, the following mathematical equations explain the description [12]:

$$f_{i,j} = f_{min} + (f_{max} - f_{min}) * rand(0,1) \quad (17)$$

$$f_{i,j} = \frac{c+v_{i,j}^t}{c+v_{g,j}^t} * f_{i,j} * \left(1 + CR_i * \frac{g_j^t - x_{i,j}^t}{\left|g_j^t - x_{i,j}^t\right| + \xi}\right) \quad (18)$$

$$v_{i,j}^{t+1} = w * v_{i,j}^t + \left(g_j^t - x_{i,j}^t\right) * f_{i,j} \quad (19)$$

$$x_{i,j}^{t+1} = x_{i,j}^t + v_{i,j}^t \quad (20)$$

C. Local Search

When bats get closer to their prey, it is logical to assume, they would decrease their loudness and increase the pulse emission rate. But apart from whatever loudness they use, the factor of loudness in the surrounding environment also needs to be considered. This means the mathematical equations are developed as follows for the new position of the bat in the local area are given by the below-mentioned equations, where rand $n(0,\sigma^2)$ is a Gaussian distribution with mean 0 and σ^2 as standard deviation [6]. At time step t, the mean loudness of all bats is A_{mean}^t.

If (rand (0, 1)>r_i) (21)

$$x_{i,j}^{t+1} = g_j^t * (1 + rand\ n(0, \sigma^2)) \quad (22)$$

and

$$\sigma^2 = |A_i^t - A_{mean}^t| + \xi$$

D. Pseudo code

The pseudo code for the novel bat algorithm is given below and is similar to [12]. This idea can be used upon to formulate the program for the CEED problem.

```
Input: N: the number of individuals (bats) contained by the population
        M: maximum number of iteration
        P: the probability of habitat selection,
        w: inertia weight,
        CR: the compensation rates for Doppler Effect in echoes
        θ: contraction–expansion coefficient
        G: the frequency of updating the loudness and pulse emission rate
        ν, φ; fmin; fmax; A0; r0: parameters in original Bat Algorithm
t = 0; Initialize the population and the related parameters.
Evaluate the objective function value of each individual.
While (t < M)
        If (rand (0, 1) < P)
                Generate new solutions using Eq. 16.
        Else
        Generate new solutions using Eqs. (17) – (20).
         End if.
        If (rand (0, 1) > ri)
                Generate a local solution around the selected
                best solution using Eqs. (21) and (22).
        End if
        Evaluate the objective function value of each
        individual.
        Update solutions, the loudness and pulse emission rate
        using Eqs. (12)–(15).
Rank the solutions and find the current best g^t .
If g^t does not improve in G time step,
Re-initialize the loudness Ai and set temporary pulse rates ri
which is a uniform random number between [0.85, 0.9].

End if

t = t + 1;
End while

   Output: the individual with the best objective function (fuel
cost function) value in the population.
```

IV. Results and Discussion

A comparison has been made between the Novel Bat Algorithm, and other algorithms considering a 6 generator bus (IEEE 30 bus) system with cubic cost functions. The bus data is taken from [2]. The results obtained using NBA are compared with the PSO algorithm (for individual pollutant analysis) and the combined pollutant analysis is compared with SA algorithm. Convergence graphs obtained are shown in this section.

A. Case 1: Individual Pollutant Analysis for SO_2

The results obtained considering the emission of sulphur dioxide alone is given in Table 1 for a load of 200 MW. The results of NBA are compared with the results obtained using PSO. The NBA is found to give lower total cost for this case. The convergence plot for this case is given in Fig. 1 for NBA.

B. Case 2: Individual Pollutant Analysis for CO_2

The results obtained considering the emission of Carbon dioxide alone is given in Table 2 for a load of 200 MW. The results of

NBA are compared with the results obtained using PSO. The NBA is found to give lower total cost for this case. The convergence plot for this case is given in Fig. 1 for NBA.

C. Case 3: Individual Pollutant Analysis for NO_x

The results obtained considering the emission of Carbon dioxide alone is given in Table 3 for a load of 200 MW. The results of NBA are compared with the results obtained using PSO. The NBA is found to give lower total cost for this case. The convergence plot for this case is given in Fig. 1 for NBA.

TABLE I: COMPARISON BETWEEN PSO AND NBA FOR SO_2

Gen. Code	PSO [6]	NBA
P_1 (MW)	54.23	50.00
P_2 (MW)	30.09	20.09
P_3 (MW)	21.06	15.04
P_4 (MW)	33.33	50.00
P_5 (MW)	30.53	24.86
P_6 (MW)	30.97	40.00
Fuel Cost ($/h)	3739.99	3,721.32
E_T of SO_2 (kg/h)	4458.15	4885.90
F_{TOTAL} ($/h)	7481.40	**4023.90**

TABLE II: COMPARISON BETWEEN PSO AND NBA FOR CO_2

Gen. Code	PSO [6]	NBA
P_1 (MW)	53.20	50.00
P_2 (MW)	29.64	21.19
P_3 (MW)	21.91	15.00
P_4 (MW)	33.62	42.01
P_5 (MW)	30.49	31.78
P_6 (MW)	31.31	40.00
Fuel Cost ($/h)	3745.38	3703.30
E_T of CO_2 (kg/h)	3697.11	3832.63
F_{TOTAL} ($/h)	7011.27	**3977.62**

TABLE III: COMPARISON BETWEEN PSO AND NBA FOR NO_X

Gen. Code	PSO [6]	NBA
P_1 (MW)	52.39	50.03
P_2 (MW)	28.71	20.00
P_3 (MW)	21.76	15.00
P_4 (MW)	33.67	42.01
P_5 (MW)	29.32	32.94
P_6 (MW)	34.52	40.00
Fuel Cost ($/h)	3751.75	3703.30
E_T of NO_x (kg/h)	3267.83	3395.08
F_{TOTAL} ($/h)	7419.86	**4074.42**

TABLE IV: COMPARISON BETWEEN SA AND NBA FOR COMBINED POLLUTANT ANALYSIS

Gen. Code	SA [2]	NBA
P_1 (MW)	50.00	50.16
P_2 (MW)	32.90	20.16
P_3 (MW)	15.00	15.56
P_4 (MW)	36.57	40.56
P_5 (MW)	30.93	31.77
P_6 (MW)	34.58	41.00
Fuel Cost ($/h)	3735.73	3703.00
E_T of SO_2 (kg/h)	4553.97	4653.34
E_T of NO_x (kg/h)	3285.64	3412.54
E_T of CO_2 (kg/h)	3714.33	3837.84
F_{TOTAL} ($/h)	14421.30	**11074.02**

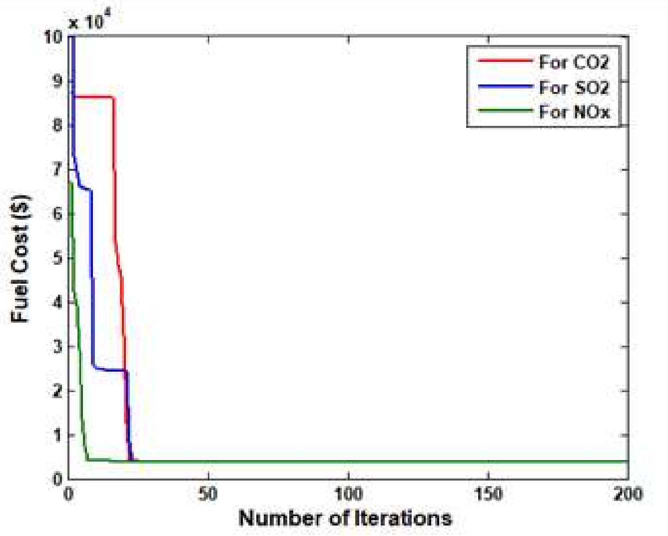

Fig. 1: Convergence graph for individual pollutant analysis using NBA.

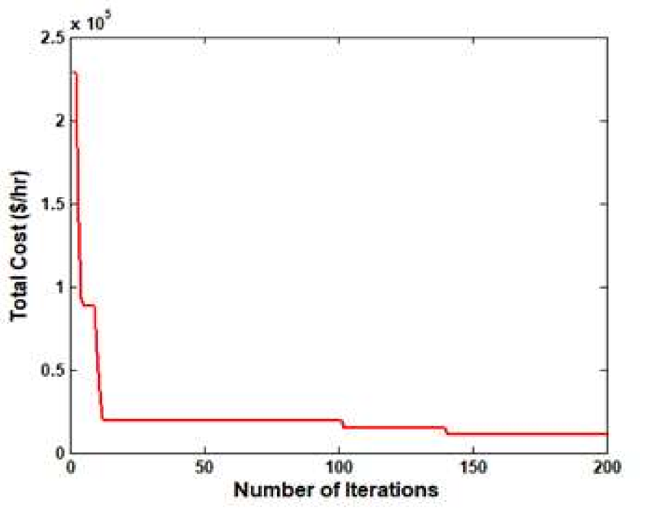

Fig. 2: Convergence curve of NBA for case 4

D. *Case 4: Combined Pollutant Analysis*

The results obtained considering the emission of all three pollutants is given in Table 4 for a load of 200 MW. The results obtained with NBA are compared with the results obtained using Simulated Annealing (SA) algorithm. The SA algorithm outperforms PSO [2], while NBA gives better solution than SA, as seen in Table 4. The NBA is found to give the lowest total cost for this case. The convergence plot for this case is given in Fig. 4 for both BA and NBA. The generation power distribution graph is shown in Fig. 2.

By considering other load demands of 150 MW,175 MW, 225 MW, it is seen that NBA performs better in giving the lowest fuel cost as well as the total cost when compared to SA.

TABLE V: COMPARISON OF RESULTS FOR DIFFERENT LOAD CONDITIONS

	Fuel Cost ($)	**SO_2 (kg/hr)**	**NO_x (kg/hr)**	**CO_2 (kg/hr)**	**Total Cost ($)**
Load=150 MW					
NBA	2700.92	3134.25	2369.21	2619.29	**8814.90**
SA	2705.21	3138.44	2379.35	2568.94	10261.49
Load=175 MW					
NBA	3173.18	3951.82	2868.91	3294.15	**10314.21**
SA	3220.51	3763.47	2789.92	3094.68	12280.04
Load=225 MW					
NBA	4307.56	5494.81	3899.15	4258.24	**14001.32**
SA	4321..51	5287.30	3781.19	4324.30	16790.69

V. CONCLUSION

In this paper, the Novel Bat Algorithm for combined economic emission dispatch problem is discussed. For the test case of a 6 generator bus system, having cubic cost functions, with a power demand in the range of 150 MW to 225 MW, this algorithm proves to be the best in giving the lowest cost, among the algorithms with which it has been compared. It can hence be concluded that NBA is a robust algorithm for the experiments performed. This method can be extended to determine its robustness for higher dimensional problems and those involving renewable sources of energy.

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