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Environmental Economic Load Dispatch with Quadratic Fuel Cost Function Using Cuckoo Search Algorithm

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Abstract

In this paper, a Cuckoo Search Algorithm (CSA) is proposed for solving environmental economic load dispatch (EELD) problem with quadratic fuel function. Cuckoo Search is a new meta-heuristic algorithm inspired from the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of other host birds of other species for solving optimization problems with promising results. However, Cuckoo Search has not been applied to EELD problem so far. Therefore, the paper presents application of CSA to the problem. The effectiveness of the proposed method is tested on several cases of dispatch and loads. The obtained result including fuel cost, emission and computation time from CSA are compared to those from other method reported in the paper. The comparison result has indicated that the proposed CSA is a very efficient method for solving EELD problem.

Keywords: *Cuckoo Search algorithm, environmental economic load dispatch, quadratic fuel cost function*

Nomenclature

a_i, b_i, c_i:	Cost coefficients of thermal unit *i*
d_i, e_i, f_i:	Emission coefficients of thermal unit *i*
B_{ij}, B_{0i}, B_{00} :	Transmission loss formula coefficients
N:	Number of online generating units
P_D :	Total load demand of the system (MW)
P_L :	Total network loss of the system (MW)
Pi:	Output power of unit *i* (MW)
P_{imin}, P_{imax}:	Lower and upper generation limits of unit *i* (MW)
w_1, w_2	Weights corresponding to the fuel cost and NOx emission objectives.

1. Introduction

The main objective of economic load dispatch (ELD) is to minimize fuel cost of thermal units while satisfying both equality and inequality constraints including load balance constraint, upper and lower generation limit on thermal units. Nowadays, emission control is also an important objective to consider along with fuel cost and utility planners are trying to improve their operating strategies to reduce pollution [1]. In fact, apart from heat, thermal units produce particulates and gaseous emissions. A

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number of substances such as CO2, SO2, NOx, dust particles etc. are emitted during the operation of thermal units. Society demands adequate and secure electricity not only at the cheapest possible price, but also at minimum level of pollutant's emission [2]. Therefore, the objective of the EELD problem is to minimize both fuel cost and the gaseous emission.

Several methods have been applied for solving ELD problem neglecting environment aspects so far. The lambda-iteration method [3-4], Hopfield neural network (HNN) [5], the enhanced Lagrangian neural network (ELANN) [6], particle Swarm Optimization (PSO) [7]. The lamda-iteration method can be valued as a simple and effective one. However, the disadvantage of the method is selection of the lamda value. In addition, in case of a large scale problem the method needs long simulation time in order to get convergence. The application of the HNN with its merit of simplicity has created difficulties in handling some kinds of inequality constraints and dealing with large-scale problems with many constraints. Moreover, the final solution of the HNN method is also sensitive to the choice of penalty factors associated with constraints. In ELANN, the dynamics of Lagrange multipliers including equality and inequality constraints were improved to guarantee its convergence to the optimal solutions, and the momentum technique was also employed in its learning algorithm to achieve fast computational time. Both HNN [5] and ELANN [6] were involved a large number of iterations for convergence. PSO is one of the modern heuristic algorithms and has a great potential to solve complex optimization problems. PSO algorithm is highly robust yet remarkably simple to implement. Thus, it is quite pertinent to apply the PSO with new modifications to achieve better optimization and handle the power system problems efficiently [8].

Recently, ELD problem has been extended by adding emission objective. Several methods including conventional and meta-heuristic methods have been applied for solving the EELD problem such as biogeography-based optimization (BBO) [8], fuzzy logic controlled genetic algorithm (FCGA) [9], Differential Evolution (DE) [10], the Non-dominated Sorting Genetic Algorithm - II (NSGA-II) [11], Improved Hopfield Neural Network Model (HNN) [12], Tabu Search (TS) [13]. This BBO algorithm is similar to other population-based optimization techniques where population of candidate solutions is represented as vector of real numbers. BBO also has fitness function to value each obtained solution and search better solution than the previous iteration. The advantage of BBO is that it can solve problem with smooth and nonsmooth fuel cost function as well as problem with complex constraints. However, BBO has the disadvantage of many parameters need to control. In FCGA, two fuzzy controllers based on some heuristics have been designed to adaptively adjust the crossover probability and mutation rate during the optimization process to improve the overall performance. The DE [10] algorithm is found to be a powerful evolutionary algorithm for global optimization in many real problems. However, there is no guaranty for this method to always obtain optimal solution. Moreover, the DE method is also slow when dealing with large-scale problems [2]. NSGA-II seems to be a powerful method through the comparisons in terms of cost and emission. However, the effectiveness of NSGA-II in terms of fast convergence is still not demonstrated. Roa-Sepulveda *et al.*, [13] extended the HNN in [12] for an Hopfield Neural Network and also used Tabu Search by linearly combining the objectives. It was observed that the weighting factor selection was complicated as each weighting factor affects the others. These authors first set the power mismatch weighting factor and then used the above method to calculate those for the emissions [11].

The cuckoo search algorithm (CSA) developed by Yang and Deb in 2009 [14] is a new meta-heuristic algorithm for solving optimization problems inspired from the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of other host birds of other species. To verify the effectiveness of the CS algorithm, Yang and Deb compared its performance with particle swarm optimization (PSO) and GA for ten standard optimization benchmark functions [14]. As observed from the obtained results, the CSA method has been outperformed both PSO and GA methods for all test functions in terms of success rate in finding optimal solution and the number of required objective function evaluations. The highlighted advantages of the CSA method are fine balance of randomization and intensification and less number of control parameters. Recently, CSA has been successfully applied for solving non-convex economic dispatch (ED) problems considering generator and system characteristics including valve point loading effects, multiple fuel options, prohibited operating zones, spinning reserve and power loss [15]. In addition, CSA has been also used for solving the ED problems in practical power system and micro grid power dispatch problem [16]. For ED problems [15, 16], CSA has been tested on many systems and obtained better solution quality than several methods in the literature such as HNN, GA, EP, Taguchi method, biogeography-based optimization, and PSO, etc. Moreover, for micro grid power dispatch problem [16], CSA also obtains higher solution quality than DE and PSO. Therefore, CSA is an efficient method for solving optimal problems.

In this paper, a cuckoo search algorithm (CSA) is proposed for solving EELD problem considering power losses in transmission systems and upper and lower generation of thermal units. The effectiveness of the proposed CSA has been tested on different systems and the obtained results have been compared to those from other methods available in the literature such as NSGA-II [11], Tabu Search (TS) [13], FCGA [9] and CGA [9].

2. Problem Formulation

The objective of the ED problem with multiple fuel options is only to minimize the total cost of thermal generating units. In the EED problem, the objective is to find a suitable fuel for each generating unit in order to minimize both the total cost and the emissions given off from thermal generating while satisfying different constraints including power balance and generation limits.

Mathematically, the problem is formulated as follows:

$$Min \sum_{i=1}^{N} F_i = \sum_{i=1}^{N} \left(w_1 F_{1i}(P_i) + w_2 F_{2i}(P_i) \right) \tag{1}$$

Where:

$$F_{1i}(P_i) = c_i P_i^2 + b_i P_i + a_i \tag{2}$$

$$F_{2i}(P_i) = f_i P_i^2 + e_i P_i + d_i \tag{3}$$

Subject to:

1. Power balance constraints:

$$\sum_{i=1}^{N} P_i - P_L - P_D = 0 \tag{4}$$

$$P_{Lk} = \sum_{i=1}^{N_1} \sum_{j=1}^{N_1} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{0i} P_i + B_{00} \tag{5}$$

2. Generator operating limits:

$$P_{i\min} \le P_i \le P_{i\max} \tag{6}$$

3. Weight constraint [17]:

$$w_1 + w_2 = 1 \tag{7}$$

3. Cuckoo Search Algorithm for EELD Problem

3.1. Calculation of Generation for Slack Thermal Unit

To guarantee that the equality constraint (4) is always satisfied, a slack generating unit 1 is arbitrarily selected and therefore its power output will be dependent on the power output of remaining *N*-1 generating units in the system. Suppose that the power output of the *N*-1 generating units are known, the power output of the slack unit *s* is calculated based on (4) as follows:

$$P_{s1} = P_D + P_L - \sum_{i=2}^{N} P_i \tag{8}$$

The power loss equation in (5) is rewritten by considering P_s as an unknown variable:

$$P_L = B_{ss} P_{s1}^2 + \left(2 \sum_{i=2}^{N} B_{si} P_i + B_{0s} \right) P_{s1} + \sum_{i=2}^{N} \sum_{j=2}^{N} P_i B_{ij} P_j + \sum_{i=2}^{N} B_{0i} P_i + B_{00} \tag{9}$$

Substituting P_L in (9) into (8), a quadratic equation is obtained:

$$A \times P_{s1}^2 + B \times P_{s1} + C = 0 \tag{10}$$

where the coefficients *A*, *B* and *C* are determined by:

$$A = B_{ss} \tag{11}$$

$$B = 2 \sum_{i=2}^{N} B_{si} P_i + B_{0s} - 1 \tag{12}$$

$$C = \sum_{i=2}^{N} \sum_{j=2}^{N} P_i B_{ij} P_j + \sum_{i=2}^{N} B_{0i} P_i + B_{00} + P_D - \sum_{i=2}^{N} P_i \tag{13}$$

The power output of the slack unit will be the positive root between the two ones obtained by solving equation (10) as below:

$$P_{s1} = \frac{-B \pm \sqrt{B^2 - 4 \times A \times C}}{2A}, \text{ where } B^2 - 4 \times A \times C \ge 0 \tag{14}$$

3.2. Cuckoo Search Algorithm Implementation

The main steps for the proposed CSA for solving EELD probelm are described as follows:

1) *Initialization:* A population of N_p host nests is represented by $X = [X_1, X_2, \dots, X_{Np}]^T$, where each nest $X_d = [P_{d2}, \dots\dots, P_{dN}]$ ($d = 1, \dots, N_p$) representing for power output of from the generating unit 2 to unit N except the slack unit P_{ds1} is initialized by:

$$X_{di} = P_{i\min} + rand_1 * (P_{i\max} - P_{i\min}) \tag{15}$$

where $rand_1$ is a uniformly distributed random number in [0, 1] for each population of the host nests.

Based on the initial population of nests, the fitness function to be minimized corresponding to each nest for the considered problem is calculated:

$$FT_d = \sum_{i=1}^{N} \left(w_1 F_{1i}(P_{id}) + w_2 F_{2i}(P_{id}) \right) + K_s (P_{ds1} - P_s^{\lim})^2 \tag{16}$$

where w_1, w_2 must satisfy (7), K_s is a penalty factor for the slack unit; P_{ds1} is power output of the slack thermal unit calculated from (14) corresponding to nest d in the population. $P_s^{\lim}$ is the limit for the slack unit in (16) is obtained by:

$$P_s^{\lim} = \begin{cases} P_{s\max} & if\ P_{ds1} > P_{1\max} \\ P_{s\min} & if\ P_{ds1} < P_{1\min} \\ P_{ds1} & \text{otherwise} \end{cases} \tag{17}$$

where P_{1max} and P_{1min} are the maximum and minimum power outputs of slack thermal unit 1, respectively.

The initial population of the host nests is set to best value of each nest $Xbest_d$ ($d = 1, \dots, N_d$) and the nest corresponding to the best fitness function in (16) is set to the best nest *Gbest* among all nests in the population.

2) *Generation of New Solution via Lévy Flights:* The new solution by each nest is calculated as follows:

$$X_d^{new} = Xbest_d + \alpha \times rand_2 \times \Delta X_d^{new} \tag{18}$$

where $\alpha > 0$ is the updated step size; $rand_2$ is a normally distributed stochastic number; and the increased value ΔX_d^{new} is determined by:

$$\Delta X_d^{new} = \nu \times \frac{\sigma_x(\beta)}{\sigma_y(\beta)} \times \left(Xbest_d - Gbest \right) \tag{19}$$

$$\nu = \frac{rand_x}{\left| rand_y \right|^{1/\beta}} \tag{20}$$

where $rand_x$ and $rand_y$ are two normally distributed stochastic variables with standard deviation $\sigma_x(\beta)$ and $\sigma_y(\beta)$ given by:

$$\sigma_x(\beta) = \left[\frac{\Gamma(1+\beta) \times \sin\left(\frac{\pi\beta}{2} \right)}{\Gamma\left(\frac{1+\beta}{2} \right) \times \beta \times 2^{\left(\frac{\beta-1}{2} \right)}} \right]^{1/\beta} \tag{21}$$

$$\sigma_y(\beta) = 1 \tag{22}$$

where β is the distribution factor ($0.3 \le \beta \le 1.99$) and $\Gamma(.)$ is the gamma distribution function.

For the newly obtained solution, its lower and upper limits should be satisfied according to the generating unit's limits:

$$X_{di}^{new} = \begin{cases} P_{i\max} & if\ X_{di} > P_{i\max} \\ P_{i\min} & if\ X_{di} < P_{i\min} \\ X_{di} & \text{otherwise} \end{cases} \tag{23}$$

The fitness function (16) will be reevaluated for the new solution to determine the newly best value of each nest *Xbest*$_d$ and the best nest of all nests *Gbest* by comparing the stored fitness values and the newly calculated ones.

3) Alien Egg Discovery and Randomization: The action of discovery of an alien egg in a nest of a host bird with the probability of p_a also creates a new solution for the problem similar to the Lévy flights. The new solution due to this action is calculated as follows:

$$X_d^{dis} = Xbest_d + K \times \Delta X_d^{dis} \tag{24}$$

where K is the updated coefficient determined based on the probability of a host bird to discover an alien egg in its nest:

$$K = \begin{cases} 1 & \text{if } rand_3 < p_a \\ 0 & \text{otherwise} \end{cases} \tag{25}$$

and the increased value ΔX_d^{dis} is determined by:

$$\Delta X_d^{dis} = rand_4 \times \left(randp_1(Xbest_d) - randp_2(Xbest_d) \right) \tag{26}$$

where $rand_3$ and $rand_4$ are the distributed random numbers in [0, 1] and $randp_1(Xbest_d)$ and $randp_2(Xbest_d)$ are the random perturbation for positions of nests in $Xbest_d$.

Similar to the solution obtained via Lévy flights, this new solution is also redefined as in (23), and each nest *Xbest*$_d$ and the best value of all nests *Gbest* are set based on fitness value obtained from (16).

4) Stopping Criteria: The proposed algorithm is terminated when the current iteration is equal to the maximum number of iteration.

4. Best Compromise Solution by Fuzzy-Based Mechanism

In the environmental economic load dispatch, there often exists a conflict among fuel cost and emission objectives. In case of minimization of only one objective, either of objectives cannot be minimized. Thus, the best compromise solution for the EELD problem needs to be determined. To obtain the best compromise, a set of optimal solutions known as Pareto-optimal solutions is found instead of only one optimal solution. The Pareto optimal front of a multi-objective problem provides decision maker several options for decision making. One of the methods to find the best compromise solution from Pareto-optimal front is fuzzy satisfying method [18]. The fuzzy goal is represented in linear membership function as follows [18]:

$$\mu(F_j) = \begin{cases} 1 & if \quad F_j \le F_{j\min} \\ \dfrac{F_{j\max} - F_j}{F_{j\max} - F_{j\min}} & if \quad F_{j\min} < F_j < F_{j\max} \\ 0 & if \quad F_j \ge F_{j\max} \end{cases} \tag{27}$$

Where F_j is the value of objective j; F_{jmax} and F_{jmin} are maximum and minimum values of objective j, respectively.

For each k non-dominated solution, the membership function is normalized as follows [19]:

$$\mu_D^k = \sum_{i=1}^{Nobj} \mu(F_i^k) \Bigg/ \sum_{k=1}^{Np} \sum_{i=1}^{Nobj} \mu(F_i^k) \tag{28}$$

where μ^k_D is the cardinal priority of kth non-dominated solution, $\mu(F^k_i)$ is membership function of objective j, N_{obj} is number of objective functions, and N_p is number of Pareto-optimal solutions.

The solution that attains the maximum membership μ^k_D in the fuzzy set is chosen as the ‘best’ solution based on cardinal priority ranking:

$$\text{Max } \{\mu^k_D : k = 1, 2, \ldots, N_p\} \tag{29}$$

5. Results and Discussions

The algorithm of HLN and LI are implemented in Matlab 7.2 programming language and executed on an Intel 1.8 GHz PC with 4 GB of Ram. The CSA is tested on two systems. The first and second systems have three and six thermal units, respectively.

5.1. System I with three thermal units

In the section, a system with three thermal units and transmission losses is considered. The data for the system is from [11]. There are three cases of dispatch for the system, economic dispatch, environmental dispatch and environmental economic dispatch. In case of the economic dispatch, w_1 and w_2 in equation (7) are set to 1 and 0, respectively. In case of the environmental dispatch, w_1 and w_2 are set to 0 and 1, respectively. In case of the environmental economic dispatch, w_1 and w_2 range from 0 to 1 with a step of 0.1 so that the sum of the two weight factors is 1. The best compromise solution of the dispatch is then determined by using Fuzzy-Based Mechanism as in section 4. The optimal solutions for the three cases of dispatch and the comparison of the obtained result are given in Tables 1, 2 and 3. As observed from Table 1correspongding to the economic dispatch, CSA and BBO [8] have the same fuel cost, which is less than that from Tabu Search [13] and NSGA-II [11]. In case of environmental dispatch given in Table 2, CSA has equal emission with BBO and less emission than NSGA-II and higher emission than Tabu Search. As indicated in Table 3, CSA and NSGA-II have the same fuel cost and emission for the environmental economic dispatch. Figures 1 shows Pareto-optimal front for fuel cost and emission.

Note that CSA takes very short computation time of around 0.1 second for reaching convergence.

Table 1. Result Comparison for the Economic Load Dispatch for System 1

Unit	Tabu Search [13]	NSGA-II [11]	BBO [8]	CSA
P1 (MW)	435.69	435.885	435.195	435.1984
P2 (MW)	298.828	299.989	299.972	299.9700
P3 (MW)	131.28	129.951	130.662	130.6606
Cost ($/h)	8344.60	8344.60	8344.59	8344.59
Emission (kg/h)	0.09863	0.0986	0.09869	0.09869
Cpu (s)	-	-	-	0.09

Table 2. Result Comparison for the Environmental Dispatch for System 1

Unit	Tabu Search [13]	NSGA-II [11]	BBO [8]	CSA
P1 (MW)	502.914	505.81	508.576	508.5804
P2 (MW)	254.294	252.951	250.446	250.4425
P3 (MW)	108.592	106.023	105.724	105.7229
Cost ($/h)	8371.14	8363.63	8365.11	8365.11
Emission (kg/h)	0.0958	0.09593	0.09592	0.09592
Cpu (s)	-	-	-	0.07

Table 3. Result Comparison for the Environmental Economic Dispatch for System 1

Unit	NSGA-II [13]	CSA
P1 (MW)	470.957	470.9502
P2 (MW)	280.663	280.7243
P3 (MW)	113.675	113.6211
Cost ($/h)	8349.72	8349.722
Emission (kg/h)	0.09654	0.09654
Cpu (s)	-	0.09

5.2. System II with Six Thermal Units

In the section, a system with six thermal units and without transmission losses are considered. There are three cases of load including 800, 1200 and 1800 MW. The data of fuel cost and emission are from [9] and [11]. Like the system 1, for the second system there are also three cases of dispatch for each case of load. The optimal solution including generation, fuel cost, emission and computation time are given in Tables 4 to 6. In case of the economic dispatch, the obtained solution is compared to that from CGAs [9] and FCGAs [9]. As observed from Table 4, CSA gets better solution in terms of fuel cost and computation time than CGAs [9] and FCGAs [9] for the three cases of load of 800, 1200 and 1800 MW. Figures 2 to 4 show Pareto-optimal front for fuel cost and emission for the case of 800 MW, 1200 MW and 1800 MW load, respectively.

Table 4. Result Comparison for the Economic Dispatch for System 2

Method	Load (MW)	Unit 1 (MW)	Unit 2 (MW)	Unit 3 (MW)	Unit 4 (MW)	Unit 5 (MW)	Unit 6 (MW)	Cost ($/h)	Cpu (s)
CGAs [9]	800	109.17	104.08	52.04	305.05	114.83	114.83	8232.89	14.46
FCGAs [9]	800	104.89	102.87	51.74	314.18	113.16	113.16	8231.03	5.62
CSA	800	100.0030	100	50	305.6251	122.0105	122.3613	8227.10	0.031
CGAs [9]	1200	142.55	117.8	58.9	515.2	182.78	182.78	11493.74	17.83
FCGAs [9]	1200	131.5	129.05	52.08	494.08	200.61	200.61	11480.03	7.43
CSA	1200	123.7606	117.6874	50	448.4274	230.0625	230.0621	11477.09	0.031
CGAs [9]	1800	222.42	190.73	95.36	555.63	367.92	367.92	16589.05	19.66
FCGAs [9]	1800	250.49	215.43	109.92	572.84	325.66	325.66	16585.85	10.44
CSA	1800	248.0009	217.7156	75.1775	588.0389	335.5298	335.5372	16579.33	0.062

Table 5. Result obtained from CSA for the Environment Dispatch for System 2

Load (MW)	Unit 1 (MW)	Unit 2 (MW)	Unit 3 (MW)	Unit 4 (MW)	Unit 5 (MW)	Unit 6 (MW)	Emission (Kg/h)	Cost ($/h)	Cpu (s)
800	100.0000	100.0000	117.9502	140.0000	171.0249	171.0249	526.3901	8333.1139	0.03
1200	176.4608	176.4608	172.1758	172.1758	251.3635	251.3635	1113.3005	11685.5856	0.04
1800	283.4604	259.3104	126.2102	412.8611	359.0789	359.0789	2511.9957	16836.1727	0.03

Table 6. Result obtained from CSA for the Environment Economic Dispatch for System 2

Load (MW)	Unit 1 (MW)	Unit 2 (MW)	Unit 3 (MW)	Unit 4 (MW)	Unit 5 (MW)	Unit 6 (MW)	Cost ($/h)	Emission (Kg/h)	Cpu (s)
800	100.0000	100.0000	66.3746	181.2369	176.1943	176.1943	8269.5117	568.8394	0.032
1200	159.9966	151.4681	76.8531	308.8486	251.4168	251.416	11517.4925	1306.6945	0.033
1800	283.4604	259.3104	126.2102	412.8611	359.0789	359.0789	16641.9013	2790.9434	0.034

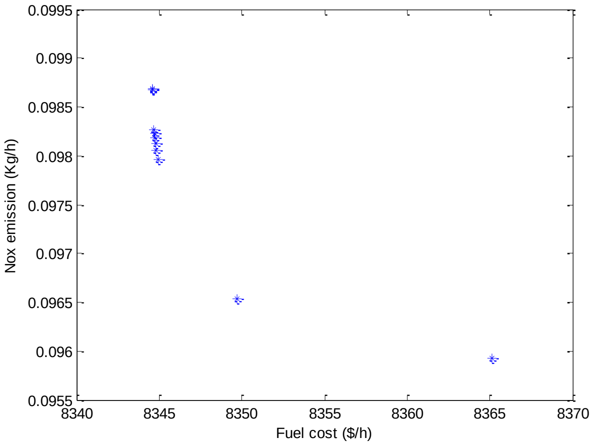

Figure 1. Pareto-optimal Front for Fuel Cost and Emission for System I

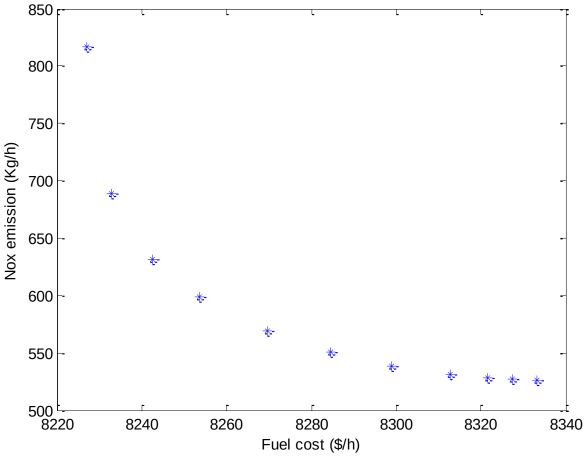

Figure 2. Pareto-optimal Front for Fuel Cost and Emission for System II with load of 800 MW

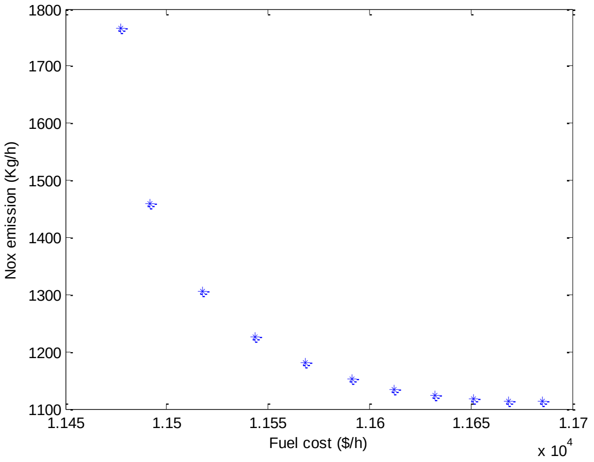

Figure 3. Pareto-optimal Front for Fuel Cost and Emission for System II with Load of 1200 MW

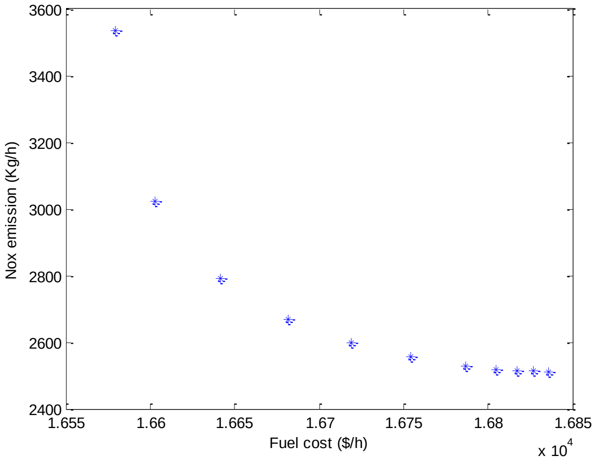

Figure 4. Pareto-optimal Front for fuel Cost and Emission for System II with Load of 1800 MW

6. Conclusion and Future Work

In this paper, a Cuckoo Search Algorithm has implemented for solving environmental economic load dispatch. CSA is a meta-heuristic algorithm with the advantage of few control parameters. The effectiveness of CSA is tested on two systems with several cases of dispatches and loads. The optimal solution from CSA compared to that from other methods has indicated that CSA is a very efficient method for solving EELD problem.

In practical systems, thermal power generating stations are the sources of carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) causing atmospheric pollution. In addition, it is more realistic to consider valve point effect on fuel cost function of thermal units. Thus, the future work will consider non-smooth fuel cost function of thermal units, divide the emission objective into three emission objectives, leading to determine a best compromise solution for two, three and four objectives.

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