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Bat Algorithm for Solving Dynamic Economic Emission Dispatch Problem

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Abstract

This paper proposes a new meta-heuristic search algorithm, called Bat Algorithm (BA). Bat algorithm is an optimization technique motivated by the echolocation behavior of natural bats in finding their foods. The proposed algorithm is presented to solve the dynamic economic emission dispatch (DEED) problem. As emission minimization is conflicting with minimum cost of generation, the DEED problem becomes a multi-objective optimization problem with conflicting objectives. The proposed algorithm is validated on 5-unit generation system for a 24 h time interval. The results proved the efficiency of the proposed method when compared with the other optimization algorithms reported in the literature.

Keywords: *Bat algorithm, dynamic economic emission dispatch, prohibited operating zones, non-smooth cost function*.

1. Introduction

The main objective of the dynamic economic dispatch (DED) problem of a power plant is to schedule generator unit outputs that are committed to meeting predicted load demand with minimum operating cost, while satisfying all system equality and inequality constraints. Hence, the DED problem is a very limited large-scale nonlinear optimization problem [1, 2]. The presence of the valve-point effect results ripples in the heat-rate curves so that the objective function becomes non-smooth, non-convex, and with multiple minima [3-5]. The fuel cost function with valve-point effects in the generating units is the accurate model of the DED problem [6, 7].

In recent years strategically utilizing available resources and achieving electricity at bargain prices without sacrificing social benefits is very important. The environmental pollution plays a major role as it had a major threat on the human society. Hence, it became compulsory to deliver electricity at a minimum cost as well as to maintain minimum level of emissions. Lowest emissions are considered as one of the objectives in combined economic and emission dispatch problems, along with cost economy. Atmospheric pollution due to release of gases such as nitrogen oxides (NO_X), carbon dioxide (CO_2), and sulphur oxides (SO_X) into atmosphere by fossil-fuel based electric power stations affects not only humans but also other forms of life such as birds, animals, plants and fish, while causes global warming too [8-11]. Generating units may have certain prohibited operating zones (POZs) due to faults in the machines themselves or instability concerns or the valve point effect. Hence, considering the effect of valve-points and POZs in generators' cost function makes the economic dispatch a non-smooth and non-convex optimization problem [12].

The emission dispatch is a short-term alternative that should be optimized, besides fuel cost goals. Thus, DEED problem can be handled as a multi-objective optimization problem and requires only small modification to include emission. Therefore, the DEED problem can be converted into a single objective problem by linear combination of various objectives using different weights. The important characteristic of the weighted sum method is that different pareto-optimal solutions can be obtained by varying the weights [13]. In [14-16] the static economic dispatch problem with prohibited operating zones has been solved. A number of reported works has considered the prohibited operating zones in DED problem [17-20], however, the emission has not considered in these papers.

Latterly, a new meta-heuristic search algorithm, called Bat Algorithm (BA) [21], has been developed by Yang. In this paper, bat algorithm has been used to solve the DEED problem considering ramp rate limits, valve-point effects, prohibited operating zones, and transmission loss. The effectiveness and potential of the proposed approach is tested on a 5-unit generation system. The results obtained by the proposed BA technique are compared with other optimization results reported in literature.

2. Problem Formulation

The objective of DEED problem is to find the optimal schedule of output powers of online generating units with predicted power demands over a certain period of time to meet the power demand at minimum both operating cost and emission simultaneously.

The objective function of the DEED problem can be formulated as follow:

$$F_T = w_1 * \sum_{t=1}^{T}\sum_{i=1}^{N} F_{i,t}(P_{i,t}) + w_2 * h * \sum_{t=1}^{T}\sum_{i=1}^{N} E_{i,t}(P_{i,t}) \qquad (1)$$

$$\text{for } i = 1,2,\cdots,N;\ t = 1,2,\ldots,T$$

where F_T is the total operating cost over the whole dispatch period, T is the number of hours in the time horizon, N is the total number of generating units, w_1 is weighting factor for economic objective such that its value should be within the range 0 and 1, and w_2 is the weighting factor for emission objective which is given by $w_2 = (1 - w_1)$, and h_i is the price penalty factor. $F_{i,t}(P_{i,t})$ and $E_{i,t}(P_{i,t})$ are the generation cost and the amount of emission for ith unit at time interval t , and $P_{i,t}$ is the real power output of generating ith unit at time period t.

The fuel cost of the ith thermal generating unit is expressed as the sum of a quadratic and a sinusoidal form with the valve-point effects taken into accout. Thus, the total generation cost is expressed as follows [12]:

$$F_{i,t}(P_{i,t}) = \begin{pmatrix} a_i P_{i,t}^2 + b_i P_{i,t} + c_i + \\ \left| e_i \times \sin\left(f_i \times \left(P_{i,\min} - P_{i,t} \right)\right) \right| \end{pmatrix} \qquad (2)$$

where the constant a_i, b_i, and c_i represents generator cost coefficients and e_i and f_i represents valve-point effect coefficients of the ith generating unit.

Utilization of thermal power plant consuming fossil fuel is with release of high amounts of NO_X, they are strongly requested by the environmental protection agency to reduce their emissions. The NO_X emission of the thermal power station having N generating units at interval t in the scheduling horizon is represented by the sum of quadratic and exponential functions of power generation of each unit. The emission due to ith thermal generating unit can be expressed as

$$E_{i,t}(P_{i,t}) = \left(\alpha_i P_{i,t}^2 + \beta_i P_{i,t} + \gamma_i + \eta_i \exp\left(\delta_i P_{i,t} \right) \right) \qquad (3)$$

where α_i ,β_i , γ_i , η_i and δ_i are emission coefficients of the ith generating unit.

The minimization of the fuel cost and emission are subjected to the following equality and inequality constraints:

2.1 Power Balance Constraint

The total generated real power should be the same as total load demand plus the total line loss.

$$\sum_{i=1}^{N} P_{i,t} = P_{D,t} + P_{L,t} \qquad (4)$$

where $P_{D,t}$ and $P_{L,t}$ are the demand and transmission loss in MW at time interval t, respectively.

The transmission loss $P_{L,t}$ can be expressed by using B matrix technique and is defined as:

$$P_{L,t} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{i,t} B_{ij} P_{j,t} \qquad (5)$$

where B_{ij} is the ij-th element of the loss coefficient square matrix of size N.

2.2 Generation Limits

The real power output of each generators should lie between minimum and maximum limits.

$$P_{i,\min} \le P_{i,t} \le P_{i,\max} \qquad (6)$$

2.3 Ramp Rate Limits

The ramp-up and ramp-down constraints can be written as:

$$P_{i,t} - P_{i,t-1} \le UR_i \qquad (7)$$

$$P_{i,t-1} - P_{i,t} \le DR_i \qquad (8)$$

where $P_{i,t}$ and $P_{i,t-1}$ are the present and previous real power outputs, respectively. UR_i and DR_i are the ramp-up and ramp-down limits of ith unit (in units of MW/time period).

To consider the ramp rate limits and real power output limits constraint at the same times, therefore, equations (6), (7) and (8) can be rewritten as follows:

$$\max\{P_{i,\min}, P_{i,t-1} - DR_i\} \le P_{i,t} \le \min\{P_{i,\max}, P_{i,t-1} + UR_i\} \qquad (9)$$

2.4 Prohibited Operating Zones

The possible operating zones of the generator can be described as follows [7, 15]:

$$P_{i,t} \in \begin{cases} P_{i,\min} \le P_{i,t} \le P_{i,1}^{l} \\ P_{i,k-1}^{u} \le P_{i,t} \le P_{i,k}^{l}, \quad k = 2,3,\ldots, pz_i \\ P_{i,pz_i}^{u} \le P_{i,t} \le P_{i,\max},\ i = 1,2,\ldots,n_{pz} \end{cases} \qquad (10)$$

where $P_{i,k}^{l}$ and $P_{i,k}^{u}$ are the lower and upper boundary of prohibited operating zone of ith unit, respectively. Here, pz_i is the number of prohibited zones of ith unit and n_{pz} is the number of units which have prohibited operating zones.

3. Bat Algorithm (BA)

Bat algorithm is a meta-heuristic approach based on the behavior of bat echolocation. The bat has the capability to find its prey in complete darkness. It was developed by

Xin-She Yang in 2010 [21]. The algorithm mimics the echolocation behavior most prominent in bats. Bats send out streams of high-pitched sounds usually short and loud. These signals then bounce off nearby objects and send back echoes. The time delay between the emission and echo helps a bat navigate and hunt. This delay is used to interpret how far away an object is. Bats use frequencies ranging from 200 to 500 kHz. In the algorithm pulse rate ranges from 0 to 1 where 0 means no emissions and 1 means maximum emissions.

Natural bats are using the echolocation behavior in locating their foods. This echolocation characteristic is copied in the virtual Bat algorithm with the following assumptions [21]:

1. All the bats are following the echolocation mechanism and they could distinguish between prey and obstacle.
2. Each bat randomly with velocity v_i at position x_i with a fixed frequency f_{min}, varying wavelength λ and loudness A_0 while searching for prey. They adjust to the frequency (or wavelength) of the transmitted pulse and set the pulse emission rate $r \in [0, 1]$, depending on the distance of the prey.
3. Although the loudness can vary in many ways, we assume that the loudness varies from a large (positive) A_0 to a minimum constant value A_{min}.

3.1 Initialization of Bat Algorithm

Initial population is generated randomly for n number of bats. Each individual of the population consists of real valued vectors with *d* dimensions [21]. The following equation is used to generate the initial population:

$$x_{ij} = x_{\min j} + rand(0,1)(x_{\max j} - x_{\min j}) \qquad (11)$$

where $i = 1,2,\cdots,n;\ j = 1,2,\cdots,d$; $x_{\min j}$ and $x_{\max j}$ are lower and upper boundaries for dimension *j* respectively.

3.2 Movement of Virtual Bats

Defined rules are necessary for updating the position x_i and velocity v_i. The new bat at the time step *t* is found by the following equations.

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \qquad (12)$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_{best}) f_i \qquad (13)$$

$$x_i^t = x_i^{t-1} + v_i^t \qquad (14)$$

where $\beta \in [0, 1]$ indicates randomly generated number, x_{best} represents current global best solutions.

For most of the applications, $f_{min} = 0$ and $f_{max} = 100$, depending the domain size of the problem of interest. Initially, each bat is randomly assigned a frequency which is drawn uniformly from $[f_{min}, f_{max}]$.

In the local search section, once the solution is selected among the best current solutions, a new solution for each bat is generated locally using a random walk.

$$x_{new} = x_{old} + \varepsilon A^t \qquad (15)$$

where $\varepsilon \in [-1, 1]$ is a random number, while $A = < A_i^t >$ is the average loudness of all the bats at this time step.

3.3 Loudness and Pulse Emission

As iteration increases, the loudness and pulse emission have to updated because when the bat gets closer to its prey then their loudness *A* usually decreases and pulse emission rate also increases. The updating equation for loudness and pulse emission is given by

$$A_i^{t+1} = \alpha A_i^t,\ r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \qquad (16)$$

where α and γ are constants. In fact, α is similar to the cooling factor of a cooling schedule in the simulated annealing. For any $0 < \alpha < 1$ and $\gamma > 0$, we have

$$A_i^t \to 0,\ r_i^t \to r_i^0 \text{ as } t \to \infty \qquad (17)$$

where α and γ are constants. Actually, α is similar to the cooling factor of a cooling schedule in the simulated annealing. For simplicity, we set $\alpha = \gamma = 0.9$ in our simulations. The basic step of BA can be summarized as pseudo code shown in Table 1.

Table 1: Pseudocode of BA

```
Bat Algorithm
Objective function $f(x), x = (x_1, \cdots, x_d)^T$
Initialize the bat population $x_i$ (i=1, 2, ..., n) and $v_i$
Define pulse frequency $f_i$ at $x_i$
Initialize pulse rates $r_i$ and the loudness $A_i$
while (t < Max number of iterations)
Generate new solutions by adjusting frequency,
and updating velocities and locations/solutions (equations (12) to (15))
    if (rand > $r_i$ )
    Select a solution among the best solutions
    Generate a local solution around the selected best solution
    end if
    Generate a new solution by flying randomly
    if (rand < $A_i$ & $f(x_i) < f(x_{best})$)
    Accept the new solutions
    Increase $r_i$ and reduce $A_i$
    end if
Rank the bats and find the current best $x_{best}$
end while
Post-process results and visualization
```

4. Simulation Results

In order to demonstrate the performance of the proposed BA technique, a 5-unit test system with non-smooth fuel cost and emission functions are used. The fuel cost coefficients including valve-point effects, emission coefficients, generation limits, ramp rate limits, prohibited operating zones, B-loss coefficients, and load demand in each interval are given in Appendix, which is taken from [22]. The demand of the system has been divided into 24 intervals. The transmission losses are calculated using B-loss coefficients formula. The parameters of algorithm used for simulation are: max generation = 100; population size = 20; A = 0.9; r = 0.1; f_{min} = 0 and f_{max} = 2.

The best solutions of the dynamic economic dispatch (DED), dynamic economic emission dispatch (DEED) and pure dynamic emission dispatch (PDED) are given in Tables 2, 3, and 4, respectively.

Table 2 shows hourly generation schedule, cost and emission obtained from DED problem. Table 4 shows hourly generation schedule, cost, and emission obtained from PDED problem. It is seen from Tables 2 and 4 that the cost is 44134.7328 $ under DED but it increases to 51848.1615 $ under PDED and emission obtained from DED is 22362.2203 lb but decreases to 17869.5089 lb under PDED. Table 3 shows hourly generation schedule, cost, and emission obtained from DEED problem. It can be seen that the cost is 45527.8020 $ which is more than 44134.7328 $ and less than 51848.1615 $, and emission is 18384.5088 lb which is less 22362.2203 lb and more than 17869.5089 lb.

Table 2: Hourly power schedule obtained from DEED (w_1=1, w_2=0)

H	P_1	P_2	P_3	P_4	P_5	Loss
1	10.0439	31.9287	106.9729	124.8960	139.6404	3.4819
2	74.9841	20.0229	112.6715	91.4722	139.7650	3.9157
3	74.9932	98.5425	112.7239	124.9689	68.5138	4.7422
4	10.0195	94.3995	100.6051	193.5738	137.5022	6.1001
5	74.9996	35.4130	30.0540	124.9325	300.0000	7.3991
6	43.8569	20.0403	112.6610	209.8138	229.5398	7.9118
7	10.0043	98.1160	87.3181	209.7648	229.4460	8.6492
8	74.9910	36.0498	112.6792	209.8587	229.5184	9.0971
9	66.2394	81.7910	112.7600	209.8070	229.5199	10.1173
10	69.3525	93.2957	112.5908	209.7989	229.5074	10.5453
11	74.9630	100.0930	114.3508	210.0912	231.5336	11.0316
12	74.9683	98.6834	113.0205	209.6883	255.3483	11.7089
13	71.2384	91.2886	112.6699	209.8203	229.5233	10.5404
14	49.5480	98.5453	112.7172	209.8348	229.5229	10.1682
15	74.9834	35.7652	112.9623	209.8668	229.5183	9.0961
16	11.5707	23.6264	112.6871	209.8742	229.5215	7.2797
17	10.0080	98.4306	106.8115	209.8069	139.7365	6.7935
18	50.2267	98.5101	112.6792	124.9042	229.5271	7.8474
19	74.9939	118.2983	120.1727	209.8577	139.7736	9.0962
20	74.9916	50.9964	149.0172	209.8095	229.5390	10.3537
21	74.9873	98.5280	161.7546	124.8742	229.5097	9.6539
22	52.0191	98.5715	112.6664	209.8108	139.7287	7.7966
23	74.9730	48.5937	55.0931	124.9534	229.5249	6.1380
24	10.0033	80.2856	112.6600	124.8192	139.7195	4.4875
Cost=44134.7328 $, Emission=22362.2203 lb, Loss=193.9514 MW						

Table 3: Hourly power schedule obtained from DEED (w_1=w_2=0.5)

H	P_1	P_2	P_3	P_4	P_5	Loss
1	74.9649	41.1638	112.7290	124.9892	59.6442	3.4911
2	73.2256	78.1338	112.6674	124.9495	50.0014	3.9777
3	74.9306	82.7000	112.6885	124.9107	84.4509	4.6807
4	74.5987	89.3581	112.6659	124.9110	134.2824	5.8161
5	74.9727	98.5380	126.2268	124.9541	139.7552	6.4469
6	74.9113	97.9210	112.7170	191.3155	138.9253	7.7901
7	74.9497	98.5139	115.9447	205.2154	139.6639	8.2876
8	74.9955	105.7457	132.8613	209.6685	139.7416	9.0126
9	74.9779	100.8709	174.7404	209.6182	139.7085	9.9158
10	74.9784	101.7613	175.0000	209.8568	152.7112	10.3077
11	74.9793	98.5858	175.0000	210.5117	171.6851	10.7619
12	74.9950	102.1222	175.0000	209.8404	189.4155	11.3731

13	74.9939	102.4202	175.0000	209.8454	152.0505	10.3099
14	74.9930	100.2559	175.0000	209.8094	139.8560	9.9144
15	74.9013	98.5178	146.5699	203.2994	139.6487	8.9371
16	74.9700	98.5318	132.6957	141.0961	139.7571	6.9606
17	74.9789	98.5777	120.4548	130.6817	139.7649	6.4580
18	74.9985	98.4945	112.6877	189.9085	139.6979	7.7872
19	74.9943	98.5374	140.0044	209.6860	139.7509	8.9730
20	74.9912	103.8292	175.0000	209.8733	150.6213	10.3150
21	74.9876	98.5394	166.8471	209.5450	139.7175	9.6366
22	74.9622	98.5389	112.7607	186.7451	139.6953	7.7022
23	72.7061	92.9189	112.6877	124.9074	129.5357	5.7558
24	74.9883	98.5299	112.7392	124.9200	56.3555	4.5330
Cost=45527.8020 $, Emission=18384.5088 lb, Loss=189.1442 MW						

Table 4: Hourly power schedule obtained from DEED (w_1=0, w_2=1)

H	P_1	P_2	P_3	P_4	P_5	Loss
1	54.6740	58.2502	116.5610	110.6038	73.3589	3.4480
2	58.0628	62.3641	121.8427	117.9907	78.6250	3.8854
3	63.5086	69.0764	130.2477	129.7476	87.0609	4.6413
4	71.1189	78.3974	141.5460	145.8156	98.9157	5.7935
5	74.9980	83.2585	147.2399	153.9115	105.0228	6.4307
6	74.9967	92.5566	159.0984	170.6050	118.3957	7.6523
7	74.9975	97.3627	162.6666	176.2421	122.8544	8.1234
8	74.9783	99.5549	168.1733	188.6116	131.5597	8.8779
9	74.9988	112.0182	175.0000	197.3385	140.5590	9.9145
10	74.9734	98.5774	175.0000	212.4520	153.3036	10.3064
11	74.9953	103.3581	175.0000	218.6061	158.8431	10.8026
12	74.9996	120.0060	175.0000	219.0983	162.3526	11.4564
13	74.9903	117.3117	175.0000	202.7007	144.3409	10.3435
14	74.9988	111.8955	175.0000	197.2632	140.7563	9.9138
15	74.9917	103.4695	169.2425	184.8491	130.3282	8.8810
16	74.9961	87.8321	152.3116	161.1402	110.6755	6.9555
17	74.9973	83.2822	147.2066	153.9341	105.0106	6.4308
18	74.9970	93.4915	159.1003	170.3234	117.7426	7.6548
19	74.9891	100.7700	167.0929	188.8860	131.1449	8.8830
20	74.9978	112.3122	175.0000	205.7578	146.2652	10.3330
21	74.9915	109.9422	169.5167	197.1170	138.0657	9.6331
22	74.9948	92.6130	158.1927	169.4372	117.3396	7.5774
23	70.7374	77.9183	140.9248	144.9133	98.2336	5.7274
24	61.8498	67.0718	127.7228	126.2536	84.5092	4.4074
Cost=51848.1615 $, Emission=17869.5089 lb, Loss=188.0731 MW						

Table 5: Comparison results for 5-unit system

Weight	Method	Cost ($)	Emission (lb)
w_1=1; w_2=0	PSO [22]	47852	22405
	DE-SQP [23]	45590	23567
	BA	44134.7328	22362.2203
w_1=w_2=0.5	PSO [22]	50893	20163
	DE-SQP [23]	46625	20527
	BA	45527.8020	18384.5088
w_1=0; w_2=1	PSO [22]	53086	19094
	DE-SQP [23]	52611	18955
	BA	51848.1615	17869.5089

Table 5 shows that the efficiency of the proposed method compares with other method for DEED problem at different weighting factors. It can be seen that both fuel cost and emission less than other method reported in the literature.

5. Conclusions

In this paper, Bat Algorithm (BA) has been successfully applied for solving the DEED problem considering ramp rate limits, valve-point effects, prohibited operating zones, and transmission loss. The effectiveness of this algorithm is demonstrated for a 5-unit generation system. The obtained results from the test systems have indicated that the proposed technique has a much better performance in terms of the lowest fuel cost and emissions than other optimization methods reported in the literature. From the results obtained it can be concluded that proposed BA based approach is a competitive technique for solving complex non-smooth optimization problems in power system operation.

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Appendix

Table A-1: Data for the 5-unit system

Quantities	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
a_i (\$/(MW)^{2}h)	0.0080	0.0030	0.0012	0.0010	0.0015
b_i (\$/MWh)	2.0	1.8	2.1	2.0	1.8
c_i (\$/h)	25	60	100	120	40
e_i (\$/h)	100	140	160	180	200
f_i (rad/MW)	0.042	0.040	0.038	0.037	0.035
α_i (lb/MW^{2}h)	0.0180	0.0150	0.0105	0.0080	0.0120
β_i (lb/MWh)	-0.805	-0.555	-1.355	-0.600	-0.555
γ_i (lb/h)	80	50	60	45	30
η_i (lb/h)	0.6550	0.5773	0.4968	0.4860	0.5035
δ_i (1/MW)	0.02846	0.02446	0.02270	0.01948	0.02075
$P_{i,\,min}$ (MW)	10	20	30	40	50
$P_{i,\,max}$ (MW)	75	125	175	250	300
UR_i (MW/h)	30	30	40	50	50
DR_i (MW/h)	30	30	40	50	50
$\mathrm{POZ}_{s\text{-}1}$	[25 30]	[45 50]	[60 70]	[95 110]	[80 100]
$\mathrm{POZ}_{s\text{-}2}$	[55 60]	[80 90]	[125 140]	[160 180]	[175 200]

Table A-2: B-loss coefficients for 5-unit system

$$B = \begin{bmatrix} 0.000049 & 0.000014 & 0.000015 & 0.000015 & 0.000020 \\ 0.000014 & 0.000045 & 0.000016 & 0.000020 & 0.000018 \\ 0.000015 & 0.000016 & 0.000039 & 0.000010 & 0.000012 \\ 0.000015 & 0.000020 & 0.000010 & 0.000040 & 0.000014 \\ 0.000020 & 0.000018 & 0.000012 & 0.000014 & 0.000035 \end{bmatrix} \text{ per MW}$$

Table A-3: Load demand for 24 hours (5-unit system)

Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)
1	410	7	626	13	704	19	654
2	435	8	654	14	690	20	704
3	475	9	690	15	654	21	680
4	530	10	704	16	580	22	605
5	558	11	720	17	558	23	527
6	608	12	740	18	608	24	463