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Bat Algorithm for Solving Non-Convex Dynamic Economic Dispatch Problems

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***Abstract*—**

This paper presents the application of Bat Algorithm (BA) for solving non-convex dynamic economic dispatch (DED) problems considering valve-point effects, the ramp rate limits and transmission losses. The practical DED problems have non-smooth cost function with equality and inequality constraints, which make the problem of finding the global optimum difficult when using any mathematical approaches. Bat algorithm is an optimization technique motivated by the echolocation behaviour of natural bats in finding their foods. The feasibility of the proposed method is validated on 5 and 10 units test system for a 24 h time interval. The results are compared with the results reported in the literature.

***Keywords*— Bat algorithm, dynamic economic dispatch, non-smooth cost functions, valve-point effects, ramp rate limits**

I. INTRODUCTION

The primary objective of the economic dispatch (ED) problem is to determine the optimal combination of power outputs of all generating units to minimize the total fuel cost while satisfying the load demand and operational constraints. It plays an important role in operation planning and control of modern power system. Dynamic economic dispatch (DED) is one of important problems in power system operation and control, which is used to determine the optimal schedule of generating outputs online so as to meet the load demand at the minimum operating cost under various system and operating constraints over the entire dispatch periods. DED is an extension of the conventional economic dispatch problem that takes into consideration the limits on the ramp rate of generating units to maintain the life of generation equipment [1, 2].

Since the DED problem was introduced, several optimization techniques and procedures have been used for solving the DED problem with complex objective functions or constraints. There were a number of classical methods that have been applied to solve this problem such as gradient projection method, Lagrange relaxation, and linear programming [3-5]. Most of these methods are not applicable for non-smooth or non-convex cost functions. To overcome this problem, many stochastic optimization methods have been employed to solve the DED problem, such as genetic algorithm (GA) [7], simulated annealing (SA) [8], differential evolution (DE) [9, 10], particle swarm optimization (PSO) [11-13], artificial bee colony (ABC) algorithm [14, 15], evolutionary programming (EP) [16], artificial immune system (AIS) [17], imperialist competitive algorithm (ICA) [18], and glowworm swarm optimization (GSO) [19]. Theses algorithms are highly efficient and cannot easily trap in to local minima. In addition they are comfortable with all types of objective functions. Researchers across the world are constantly working to develop still efficient algorithms by copying the behaviour of nature/species. Bat algorithm is one such algorithm for optimizing engineering tasks.

In this paper, bat algorithm is proposed for achieving improved results in the non-convex DED problem. This algorithm is with less number of operators and hence can be easily coded in any programming language. To prove the strength of this algorithm its performance is compared with other algorithms.

II. DED PROBLEM FORMULATION

The objective of DED 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 operating cost.

The fuel cost function of the generating unit is expressed as a quadratic function of real power generation. The objective function of the DED problem is

$$\min F_T = \sum_{t=1}^{T}\sum_{i=1}^{N} F_{i,t}(P_{i,t}) = \sum_{t=1}^{T}\sum_{i=1}^{N}\left(a_i P_{i,t}^2 + b_i P_{i,t} + c_i\right) \quad \text{for } i = 1,2,\cdots,N;\ t = 1,2,\ldots,T \tag{1}$$

where $F_{i,t}$ is the fuel cost of unit i at time interval t in \$/hr, a_i, b_i, and c_i are the cost coefficients of generating unit i, $P_{i,t}$ is the real power output of generating unit i at time period t in MW, and N is the number of generators. T is the total number of hours in the operating horizon.

The valve-point effects are taken into consideration in the DED problem by superimposing the basic quadratic fuel-cost characteristics with the rectified sinusoid component as follows [6]:

$$\min F_T = \sum_{t=1}^{T}\sum_{i=1}^{N} F_{i,t}(P_{i,t}) = \sum_{t=1}^{T}\sum_{i=1}^{N}\left(a_i P_{i,t}^2 + b_i P_{i,t} + c_i + \left|e_i \times \sin\left(f_i \times \left(P_{i,\min} - P_{i,t}\right)\right)\right|\right) \tag{2}$$

where F_T is total fuel cost of generation in ($/hr) including valve point loading, e_i, f_i are fuel cost coefficients of unit i reflecting valve-point effects.

The fuel cost is minimized subjected to the following constraints:

2.1 Active Power Balance Equation

For power balance, an equality constraint should be satisfied. The total generated power should be the same as total load demand plus the total line loss.

$$\sum_{i=1}^{N} P_{i,t} = P_{D,t} + P_{L,t} \tag{3}$$

where $P_{D,t}$ and $P_{L,t}$ are the load 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 by (4) as,

$$P_{L,t} = \sum_{i=1}^{n}\sum_{j=1}^{n} P_{i,t} B_{ij} P_{j,t} + \sum_{i=1}^{n} B_{0i} P_{i,t} + B_{00} \tag{4}$$

where B_{ij}, B_{0i}, and B_{00} are coefficient of transmission loss.

2.2 Minimum and Maximum Power Limits

Generation output of each generator should lie between minimum and maximum limits. The corresponding inequality constraint for each generator is

$$P_{i,\min} \le P_{i,t} \le P_{i,\max} \tag{5}$$

where $P_{i,\,min}$ and $P_{i,\,max}$ are the minimum and maximum real power output of unit i in MW, respectively.

2.3 Ramp Rate Limits

The actual operating ranges of all on-line units are restricted by their corresponding ramp rate limits. The ramp-up and ramp-down constraints can be written as (6) and (7), respectively.

$$P_{i,t} - P_{i,t-1} \le UR_i \tag{6}$$

$$P_{i,t-1} - P_{i,t} \le DR_i \tag{7}$$

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

To consider the ramp rate limits and power output limits constraints at the same time, therefore, eqs. (5), (6) and (7) can be rewritten as follows:

$$\max\{P_{i,\min}, P_{i,t-1} - DR_i\} \le P_{i,t} \le \min\{P_{i,\max}, P_{i,t-1} + UR_i\} \tag{8}$$

III. BAT ALGORITHM (BA)

Bat Algorithm is a metaheuristic approach that is based echolocation behavior of bats. The bat has the capability to find its prey in complete darkness. It was developed by Xin-She Yang in 2010 [20]. 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 [20]:

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 the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission $r \in [0, 1]$, 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 [20]. The following equation is used to generate the initial population:

$$x_{ij} = x_{\min j} + rand(0,1)(x_{\max j} - x_{\min j}) \tag{9}$$

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.

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \tag{10}$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_{best})\, f_i \tag{11}$$

$$x_i^t = x_i^{t-1} + v_i^t \tag{12}$$

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}].

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

$$x_{new} = x_{old} + \varepsilon A^t \tag{13}$$

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.

The update of the velocities and positions of bats have some similarity to the procedure in the standard particle swarm optimization as f_i essentially controls the pace and range of the movement of the swarming particles. To a degree, BA can be considered as a balanced combination of the standard particle swarm optimization and the intensive local search controlled by the loudness and pulse rate.

3.3 Loudness and Pulse Emission

Furthermore, the loudness A_i and the rate r_i of pulse emission have to be updated accordingly as the iterations proceed. As the loudness usually decreases once a bat has found its prey, while the rate of pulse emission increases, the loudness can be chosen as any value of convenience. Usually, A_0 = 100 and A_{min} = 1. For simplicity, we can also use A_0 = 1 and A_{min} = 0, assuming A_{min} = 0 means that a bat has just found the prey and temporarily stop emitting any sound. Now we have

$$A_i^{t+1} = \alpha A_i^t,\; r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \tag{14}$$

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

$$A_i^t \to 0,\; r_i^t \to r_i^0 \text{ as } t \to \infty \tag{15}$$

In the simplicity case, we can use $\alpha = \gamma$, and we have used $\alpha = \gamma = 0.9$ in our simulations. The choice of parameters requires some experimenting. Initially, each bat should have different values of loudness and pulse emission rate, and this can be achieved by randomization.

Pseudo Code of 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 (10) to (13))
    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
Postprocess results and visualization

IV. SIMULATION RESULTS AND DISCUSSIONS

The DED problem was solved using the BA method and its performance is compared with other methods reported in recent literature. The proposed technique has been applied to 5 and 10 unit test systems. The algorithm was implemented in MATLAB 7.1 on a Pentium IV personal Computer with 3.6 GHz speed processor and 2 GB RAM. For all cases, the dispatch horizon is selected as one day with 24 dispatch periods of each one hour. 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.

1) Case 1: 5-unit system

The first test system is a 5-unit test system. The technical data of the units are taken from [10]. In this test system, valve-point effect, the ramp rate limits, and transmission losses are considered. The load demand for each time interval over the scheduling period is given in Table 1. The optimal dispatch of real power for the given scheduling horizon using BA method is given in Table 2. The best solution obtained through the proposed method is compared to those reported in the recent literature. The best total production cost obtained using proposed method is $ 40352.6347 and the total power loss is 193.8341 MW. Table 3 shows the comparison results for different methods.

Table 1 Load demand for 24 hours (case 1)

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

Table 2 Best scheduling of 5-unit system using BA method

Hour	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	Cost ($)	Ploss (MW)
1	14.0510	85.0446	54.8269	125.6127	134.1362	1205.9293	3.6714
2	15.9291	91.0166	86.1557	78.0821	167.8817	1268.8903	4.0651
3	14.6458	44.6109	143.0644	177.2619	100.1708	1374.2243	4.7538
4	17.7484	86.9480	100.4192	154.9648	175.8831	1486.6444	5.9634
5	21.7670	72.6640	115.3090	141.5499	213.2802	1555.7881	6.5701
6	18.5974	63.4878	145.6345	169.2065	218.8117	1680.3834	7.7380
7	19.3901	62.1851	136.4576	204.6087	211.6338	1722.4035	8.2754
8	22.8183	91.9312	131.9272	207.3034	209.1008	1786.1019	9.0809
9	61.1008	128.1536	107.8089	209.2001	193.9517	1888.8742	10.2151
10	29.6329	74.0345	131.5171	264.8546	214.6458	1918.1107	10.6849
11	24.1329	77.4931	146.5001	233.8198	249.0912	1957.6404	11.0371
12	28.0449	93.7073	181.6198	184.3814	263.7451	2009.6506	11.4985
13	26.1476	98.5444	111.9066	241.4854	236.6861	1913.1297	10.7701
14	34.9753	96.4484	152.2538	172.1577	244.1714	1881.3472	10.0066
15	42.5956	90.3020	127.1199	175.4107	227.5823	1790.5842	9.0105
16	18.3984	101.2354	134.3800	154.6417	178.4156	1607.9980	7.0710
17	35.1232	109.0514	33.1484	233.6787	154.2872	1566.8895	7.2889
18	18.6057	87.2695	104.3375	193.3232	212.4108	1674.7625	7.9467
19	23.9399	97.3191	112.7094	189.2190	239.9980	1787.8770	9.1854
20	31.7440	59.6784	125.8263	258.7984	238.6469	1922.1099	10.6939
21	28.2083	54.2909	224.2158	209.9418	172.9634	1870.3499	9.6202
22	20.4198	98.1342	112.6735	172.4761	209.1007	1666.2988	7.8042
23	22.9462	72.0674	88.4232	176.7147	172.7902	1481.6466	5.9418
24	28.1359	80.2713	22.5524	169.2191	167.7623	1335.4800	4.9410
Total						**40352.6347**	**193.8341**

Table 3 Comparison of results for 5-unit system

Method	Best cost ($)	Method	Best cost ($)
SA [8]	47356	AIS [17]	44385.43
DE [9]	43213	ICA [18]	43117.05
PSO [11]	50124	GSO [19]	43414.12
ABC [14]	44045.83	Proposed method	**40352.6347**

2) Case 2: 10-unit system

The second test system is a 10-unit test system. In this case, generator capacity limits, ramp rate constraints and valve-point effects are considered. The transmission losses are ignored in this case for sake of comparison. The data for this system can be found from [10]. The load demand for each time interval over the scheduling period is given in Table 4. The optimal dispatch of real power for the given scheduling horizon using BA technique is given in Table 5. The best solution obtained through the proposed method is compared to those reported in the recent literature are shown in Table 6.

The best total production cost obtained using proposed method is $ 1004802.8385. It clear from the table that the proposed method produces much better results compared to recently reported different method for solving DED problems.

Table 4 Load demand for 24 hours (case 2)

Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)
1	1036	7	1702	13	2072	19	1776
2	1110	8	1776	14	1924	20	2072
3	1258	9	1924	15	1776	21	1924
4	1406	10	2072	16	1554	22	1628
5	1480	11	2146	17	1480	23	1332
6	1628	12	2220	18	1628	24	1184

Table 5 Best scheduling of 10-unit system using BA method

Hour	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	P6 (MW)	P7 (MW)	P8 (MW)	P9 (MW)	P10 (MW)
1	150.1437	135.6241	186.8148	60.0030	91.3936	160.0000	130.0000	47.0201	20.0007	55.0000
2	150.0977	135.5318	194.9087	60.0411	73.0262	160.0000	130.0000	71.3946	80.0000	55.0000
3	150.1847	309.5149	204.2399	60.0694	121.9702	160.0000	130.0000	47.0140	20.0069	55.0000
4	150.0153	460.0000	117.9727	60.0084	73.0036	160.0000	130.0000	120.0000	80.0000	55.0000
5	150.2150	396.7918	340.0000	60.0006	120.9637	160.0000	130.0000	47.0062	20.0228	55.0000
6	365.6462	327.5377	340.0000	60.0030	122.8048	160.0000	130.0000	47.0075	20.0007	55.0000
7	186.9878	460.0000	340.0000	60.0031	243.0000	160.0000	130.0000	47.0085	20.0006	55.0000
8	260.9845	460.0000	340.0000	60.0092	243.0000	160.0000	130.0000	47.0052	20.0011	55.0000
9	335.9969	460.0000	340.0000	60.0013	243.0000	160.0000	130.0000	120.0000	20.0018	55.0000
10	469.9758	460.0000	340.0000	99.4878	243.0000	160.0000	130.0000	94.4305	20.1059	55.0000
11	456.5050	460.0000	340.0000	300.0000	177.4915	160.0000	130.0000	47.0033	20.0001	55.0000
12	392.0000	460.0000	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	20.0000	55.0000
13	469.9998	460.0000	340.0000	73.9902	243.0000	160.0000	130.0000	120.0000	20.0100	55.0000
14	406.2369	460.0000	340.0000	60.0012	172.7606	160.0000	130.0000	120.0000	20.0013	55.0000
15	187.9979	460.0000	340.0000	60.0008	243.0000	160.0000	130.0000	120.0000	20.0013	55.0000
16	150.0729	397.1680	340.0000	60.0366	172.1834	160.0000	130.0000	69.5315	20.0077	55.0000
17	226.6218	318.5209	340.0000	60.0080	122.8447	160.0000	130.0000	47.0042	20.0004	55.0000
18	150.0016	460.0000	303.5427	60.0046	169.4423	160.0000	130.0000	120.0000	20.0087	55.0000
19	303.2317	417.7469	340.0000	60.0063	243.0000	160.0000	130.0000	47.0102	20.0049	55.0000
20	469.9992	460.0000	340.0000	74.0001	243.0000	160.0000	130.0000	120.0000	20.0007	55.0000
21	429.3699	460.0000	340.0000	60.0193	222.5969	160.0000	130.0000	47.0052	20.0086	55.0000
22	226.2513	409.8117	340.0000	60.0027	172.5539	160.0000	130.0000	54.3139	20.0665	55.0000
23	150.0309	208.9836	184.9744	60.0053	243.0000	160.0000	130.0000	120.0000	20.0059	55.0000
24	150.0485	257.2140	205.3955	60.0044	99.1877	160.0000	130.0000	47.1015	20.0485	55.0000

Total generation cost ($) = ***1004802.8385***

Table 6 Comparison of results for 10-unit system

Method	Best cost ($)	Method	Best cost ($)
Hybrid EP-SQP [16]	1031746	ICA [18]	1018467.49
AIS [17]	1021980	MABC [15]	1022205.6846
TVAC-IPSO [13]	1018217.224	IDE [10]	1026269
Hybrid PSO-SQP [12]	1027334	Proposed method	**1004802.8385**

V. CONCLUSIONS

In this paper, a simple and an efficient optimization technique based on BA is addressed for solving non-convex dynamic economic dispatch problems considering valve-point effects, the ramp rate limits and transmission losses. The effectiveness of the proposed method is illustrated by using a 5-unit and 10-unit test systems and compared with the results obtained from other method. It is evident from the comparison that the proposed technique provides better results than other methods in terms of minimum production cost.

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