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NON-CONVEX ECONOMIC LOAD DISPATCH PROBLEMS USING NOVEL BAT ALGORITHM

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ABSTRACT

In this paper a novel bat algorithm (NBA) is proposed for solving non-convex economic load dispatch (ELD) problems so as to minimize the total generation cost when considering the linear and non linear constraints. The proposed algorithm combines the bats' habitat selection and their self-adaptive compensation for Doppler effects in echoes into the basic bat algorithm (BA). The selection of bats' habitat is modeled as the selection between their quantum behaviors and mechanical behaviors. Many nonlinear characteristics of the power generators and practical constraints, such as power loss, ramp rate limits, prohibited operating zones and valve-point effects, are considered. The effectiveness and feasibility of the proposed method are demonstrated by two real power systems and compared with other optimization algorithms reported in literature.

Keywords: *Novel Bat Algorithm, Non-Convex Economic Load Dispatch, Ramp Rate Limits, Prohibited Operating Zones, Valve-Point Effects*

1. INTRODUCTION

Modern power utilities are expected to generate power at a minimum cost. The generated power has to meet the load demand and transmission losses. Economic load dispatch (ELD) is one of the important optimization problems in power system that has the objective of dividing the power demand among the online generators economically while satisfying various constraints [1]. Since the cost of the power generation is prohibitive, an optimal dispatch saves a considerable amount of money. Traditional algorithms like lambda iteration, gradient method, base point participation factor, and Newton method can solve the ELD problems effectively if and only if the fuel-cost curves of the power generation are piece-wise linear and monotonically increasing [2].

The basic ELD problem considers the power balance constraint apart from the generating capacity limits. However, a practical ELD must take ramp rate limits, prohibited operating zones, valve-point effects, and multi-fuel options into consideration to provide the completeness for the ELD formulation. Dynamic programming (DP) [3] can solve such type of problems, but it suffers from the curse of dimensionality. Over the past few decades, as an alternative to the conventional mathematical approaches, many salient methods have been developed for ELD problem such as genetic algorithm (GA) [4], tabu search (TS) [5], simulated annealing (SA) [6], neural network (NN) [7], evolutionary programming (EP) [8, 9], particle swarm optimization (PSO) [10]-[13], biogeography-based optimization (BBO) [14, 15], differential evolution (DE) [16, 17], artificial bee colony (ABC) algorithm [18], harmony search (HS) algorithm [19], and firefly algorithm (FA) [20].

Nowadays, to find out the optimized solution of complex problem evolutionary algorithms are used over algorithmic models. Meta-heuristic Algorithms are based on natural phenomenon and are suitable for complex optimization problems. These algorithms solve the optimization problem according to population and keep on searching and evaluating for a number of times until an optimized result is obtained. New algorithms developed are either nature inspired or are dependent on the behavior of animals. Apart from development of new optimization algorithms, many new variations of a particular algorithm are being continuously developed. One such instance is the bat algorithm (BA), which was originally proposed in [21]-[23], and has seen a variety of modifications being incorporated to find which among them proves to be most optimal. In other words, variations of the same algorithm are developed to determine the best solution of a particular problem in a particular field of study. In this paper, a novel bat algorithm (NBA) has been discussed [24] and applied for an ELD problem.

In this paper, a novel and efficient approach is proposed to solve the non-convex ELD problems using a NBA technique. The performance of the proposed approach has been demonstrated on two different test systems, i.e. 6-unit and 15-unit systems. Obtained simulation results demonstrate that the proposed method provides very remarkable results for solving the ELD problem. The results have been compared to other method reported in the literature. The rest of the paper is organized as follows. After this introduction, section 2 describes the problem formulation of ELD. In section 3, bat algorithm and the proposed NBA technique are detailed. Simulation results are presented in section 4 and section 5 provides a conclusion.

2. PROBLEM FORMULATION

The ELD problem having an objective function minimize the total generation cost while fulfilling various constraints when supplying the required load demand of a power system. The objective function is given by (1) as follows:

$$F_T = \sum_{i=1}^{n} F_i(P_i) = \sum_{i=1}^{n} \left(a_i P_i^2 + b_i P_i + c_i \right) \qquad (1)$$

where F_T is total fuel cost of generation in the system ($/hr), a_i, b_i, and c_i are the cost coefficient of the i-th generator, P_i is the power generated by the i-th unit and n indicate the number of generators.

2.1 Active Power Balance

The active power balance is an equality constraint. In which the equilibrium is met when the total power generation must equals the total power demand P_D and the real power loss P_{Loss} in transmission lines. This is known as power balance constraint can be expressed as given in (2),

$$P_D = \sum_{i=1}^{n} P_i - P_{Loss} \qquad (2)$$

The transmission losses P_{Loss} can be calculated by using B matrix technique and is defined by (3) as,

$$P_{Loss} = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \qquad (3)$$

where B_{ij} is coefficient of transmission losses and the B_{0i} and B_{00} is matrix for loss in transmission which are constant under certain assumed conditions.

2.2 Generation Limits

For normal system operations, real power output of each generator is within its lower and upper bounds and is known as generation capacity constraint is given by (4)

$$P_i^{\min} \le P_i \le P_i^{\max} \quad \text{for } i = 1,2,\Lambda\ ,n \qquad (4)$$

where $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum outputs of i-th generator, respectively.

2.3 Ramp Rate Limits

By considering generator ramp rate limits, the effective real power operating limits restricted by their corresponding ramp rate limits. The ramp-up and ramp-down constraints can be written as (5) and (6), respectively.

$$P_i(t) - P_i(t-1) \le UR_i \qquad (5)$$

$$P_i(t-1) - P_i(t) \le DR_i \qquad (6)$$

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

To consider the ramp rate limits and power output limits constraints at the same time, therefore, equations (4), (5) and (6) can be rewritten as follows:

$$\begin{aligned} &\max\{P_i^{\min}, P_i(t-1) - DR_i\} \le P_i(t) \le \\ &\min\{P_i^{\max}, P_i(t-1) + UR_i\} \end{aligned} \qquad (7)$$

2.4 Prohibited Operating Zones

The generating units with prohibited operating zones have discontinuous and nonlinear cost characteristics. This characteristic can be formulated in ELD problems as follows:

$$P_i \in \begin{cases} P_i^{\min} \le P_i \le P_{i,1}^{l} \\ P_{i,k-1}^{u} \le P_i \le P_{i,k}^{l}, \quad k = 2,3,\mathrm{K}\ , pz_i \\ P_{i,pz_i}^{u} \le P_i \le P_i^{\max}, \ i = 1,2,\mathrm{K}\ , n_{pz} \end{cases} \qquad (8)$$

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

2.5 Valve-Point Effects

The generating units with multi-valve steam turbines exhibit a greater variation in the fuel-cost functions [14]. The valve-point effects are taken into consideration in the ELD problem by superimposing the basic quadratic fuel-cost characteristics with the rectified sinusoidal component as follows:

$$F_T = \sum_{i=1}^{n} F(P_i) = \sum_{i=1}^{n} \left(\begin{array}{l} a_i P_i^2 + b_i P_i + c_i + \\ \left| e_i \times \sin\left(f_i \times \left(P_i^{\min} - P_i \right) \right) \right| \end{array} \right) \quad (9)$$

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

3. META-HEURISTIC OPTIMIZATION

3.1 Bat Algorithm (BA)

Bat Algorithm is a meta-heuristic 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 [21]. The algorithm mimics the echolocation behavior most prominent in bats. Bat fly randomly in the air or in the process of searching for prey by using echolocation to catch food and to avoid obstacles. This echolocation characteristic is copied in the virtual BA with the following assumptions [21, 22]:

(1) All bats use echolocation mechanism to sense distance 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 loudness may vary in many ways, it is assumed that the loudness varies from a large (positive) A_0 to a minimum constant value A_{min}.

3.1.1 Initialization of bat algorithm

Initialization population of bats generated randomly in between the lower and upper boundary can be achieved by the following equation [23].

$$x_{ij} = x_{\min j} + rand(0,1)(x_{\max j} - x_{\min j}) \quad (10)$$

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

3.1.2 Movement of virtual bats

In the BA, the step size of the solution is controlled with the frequency factor. It is generated randomly in between the minimum and maximum frequency [f_{min}, f_{max}]. Velocity of a solution is proportional to frequency and new solution depends on its new velocity and it is represented as:

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \quad (11)$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_{best}) f_i \quad (12)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (13)$$

where $\beta \in [0, 1]$ indicates randomly generated number, x_{best} represent current global best solutions. For local search part of algorithm (exploitation) one solution is selected among the selected best solutions and random walk is applied.

$$x_{new} = x_{old} + \varepsilon A^t \quad (14)$$

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

3.1.3 Loudness and pulse emission

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

$$A_i^{t+1} = \alpha A_i^t \quad (15)$$

$$r_i^{t+1} = r_i^0 [1 - \exp(-\gamma t)] \quad (16)$$

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 Pseudo Code of BA

Bat algorithm

Objective function $f(x), x = (x_1, \Lambda, x_d)^T$
Initialization the bat population x_i (i=1, 2, ..., n) and velocity v_i
Define pulse frequency f_i at x_i
Initialization 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 (11) to (13))
  if *(rand > r_i)*
  Select a solution among the best solutions
  Generate a local solution around the current 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
Ranks the bats and find current best x_{best}
end while
Postprocess results and visualization

3.2 Novel Bat Algorithm (NBA)

In the 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 fact, this is not always the case. In NBA [24], Doppler Effect has been included in the algorithm. Each virtual bat in the proposed algorithm can also adaptively compensate for the Doppler effects 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 offset for Doppler Effects in echoes. They can adapt and adjust their compensation rate depending upon the proximity of their targets.

The pseudo code of the NBA is presented in Table 2.

Table 2 Pseudo Code of NBA

Novel bat algorithm

Objective function $f(x), x = (x_1, \Lambda, x_d)^T$
Initialization the bat population x_i (i=1, 2, …, n) and v_i
Define pulse frequency f_i at x_i
Initialization pulse rates r_i and the loudness A_i
$t = 0$;
while ($t < M$)
if (*rand (0, 1)* < *P*)
Generate new solution using (17)
else
Generate new solution using (18) – (21)
end if
if (*rand (0, 1)* > r_i)
Generate a local solution around the selected best solution using (22) and (23)
end if
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 solutions and find the current best x_{best}
if *x_{best} does not improve in G time step,*
Reinitialize the loudness A_i and set temporary pulse rate r_i which is a uniform random number between [0.85, 0.9].
end if
$t = t + 1$;
end while
Output results and visualization

3.2.1 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. During the process of search, according to certain probability of mutation p_m, some bats will be mutated with quantum behavior [24]; these bats are updated with the following formulas:

$$x_{ij}^{t+1} = \begin{cases} g_j^t + \theta * \left|mean_j^t - x_{ij}^t\right| * \ln\left(\frac{1}{u_{ij}}\right); \\ if\ rand_j(0,1) < 0.5 \\ g_j^t - \theta * \left|mean_j^t - x_{ij}^t\right| * \ln\left(\frac{1}{u_{ij}}\right); \\ otherwise \end{cases} \tag{17}$$

3.2.2 Mechanical behavior of bats

If the speed of sound in the air is 340 m/s, then with 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 ∊ [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 [24]:

$$f_{ij} = f_{min} + (f_{max} - f_{min}) * rand(0,1) \tag{18}$$

$$f_{ij} = \frac{c + v_{ij}^t}{c + g_j^t} * f_{ij} * \left(1 + CR_i * \frac{g_j^t - x_{ij}^t}{\left|g_j^t - x_{ij}^t\right| + \xi}\right) \quad (19)$$

$$v_{ij}^{t+1} = w * v_{ij}^t + \left(g_j^t - x_{ij}^t\right) * f_{ij} \quad (20)$$

$$x_{ij}^{t+1} = x_{ij}^t + v_{ij}^t \quad (21)$$

3.2.3 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 [24]. At time step t, the mean loudness of all bats is A_{mean}^t .

$$\text{If } \left(rand(0,1) > r_i\right) \quad (22)$$

$$x_{ij}^{t+1} = g_j^t * (1 + rand\ n(0, \sigma^2)) \quad (23)$$

$$\sigma^2 = \left|A_i^t - A_{mean}^t\right| + \xi \quad (24)$$

4. SIMULATION RESULTS

To verify the feasibility of the proposed technique, two different power systems were tested: (1) 6-unit system considering power loss, ramp rate limits and prohibited operating zones; and (2) 15-unit system with valve-point effects and transmission losses.

Test Case 1:

The system consists of six thermal generating units. The total load demand of the power system is 1263 MW. The parameters of all thermal units are presented in Tables 3 and 4 [10], respectively.

The coefficient of transmission losses are calculated by B matrix loss formula which for 6-unit system is given as:

$$B_{ij} = \begin{bmatrix} 0.0017 & 0.0012 & 0.0007 & -0.0001 & -0.0005 & -0.0002 \\ 0.0012 & 0.0014 & 0.0009 & 0.0001 & -0.0006 & -0.0001 \\ 0.0007 & 0.0009 & 0.0031 & 0.0000 & -0.0010 & -0.0006 \\ -0.0001 & 0.0001 & 0.0000 & 0.0024 & -0.0006 & -0.0008 \\ -0.0005 & -0.0006 & -0.0010 & -0.0006 & 0.0129 & -0.0002 \\ -0.0002 & -0.0001 & -0.0006 & -0.0008 & -0.0002 & 0.0150 \end{bmatrix}$$

$$B_{0i} = 1.0e^{-3} * [-0.3908 \ -0.1297 \ 0.7047 \ 0.0591 \ 0.2161 \ -0.6635]$$

$$B_{00} = 0.0056$$

The obtained results for the 6-unit system using the NBA technique are given in Table 5 and the results are compared with other methods reported in literature, including GA, PSO, NPSO and MHS [10, 12, 19]. It can be observed that NBA technique can get generation cost of 1544.0752 ($/hr) and power losses of 12.4443 (MW), which is the best solution among all the methods. Note that the active power outputs of the generators are all within the generator's permissible output limit. The convergence characteristic of NBA technique on test case 1 is shown in Figure 1.

Table 3 Cost Coefficients and Unit Operating Limits

Unit	P_i^{min} (MW)	P_i^{max} (MW)	a	b	c
1	100	500	0.0070	7.0	240
2	50	200	0.0095	10.0	200
3	80	300	0.0090	8.5	220
4	50	150	0.0090	11.0	200
5	50	200	0.0080	10.5	220
6	50	120	0.0075	12.0	190

Table 4 Ramp Rate Limits and Prohibited Operating Zones

Unit	P_i^0 (MW)	UR_i (MW/h)	DR_i (MW/h)	Prohibited zones (MW)
1	440	80	120	[210, 240] [350, 380]
2	170	50	90	[90, 110] [140, 160]
3	200	65	100	[150, 170] [210, 240]
4	150	50	90	[80, 90] [110, 120]
5	190	50	90	[90, 110] [140, 150]
6	110	50	90	[75, 85] [100, 105]

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Table 5 Comparison of the Best Results of Each Methods (P_D = 1263 MW)

Unit Output	GA [10]	PSO [10]	NPSO [12]	MHS [19]	BA	NBA
P1 (MW)	474.8066	447.4970	447.4734	447.5039	448.0226	447.3936
P2 (MW)	178.6363	173.3221	173.1012	173.3188	173.7490	173.2371
P3 (MW)	262.2089	263.0594	262.6804	263.4629	262.7504	263.3882
P4 (MW)	134.2826	139.0594	139.4156	139.0650	139.4533	139.0040
P5 (MW)	151.9039	165.4761	165.3002	165.4739	164.2236	165.3759
P6 (MW)	74.1812	87.1280	87.9761	87.1338	87.5686	87.0455
Total power output (MW)	1276.0217	1275.9584	1275.950	1275.9583	1275.7675	1275.4443
Generation cost ($/hr)	15459.00	15450.00	15450.00	15449.8995	15447.6779	15443.0752
Power losses (MW)	13.0217	12.9584	12.9470	12.9582	12.7675	12.4443

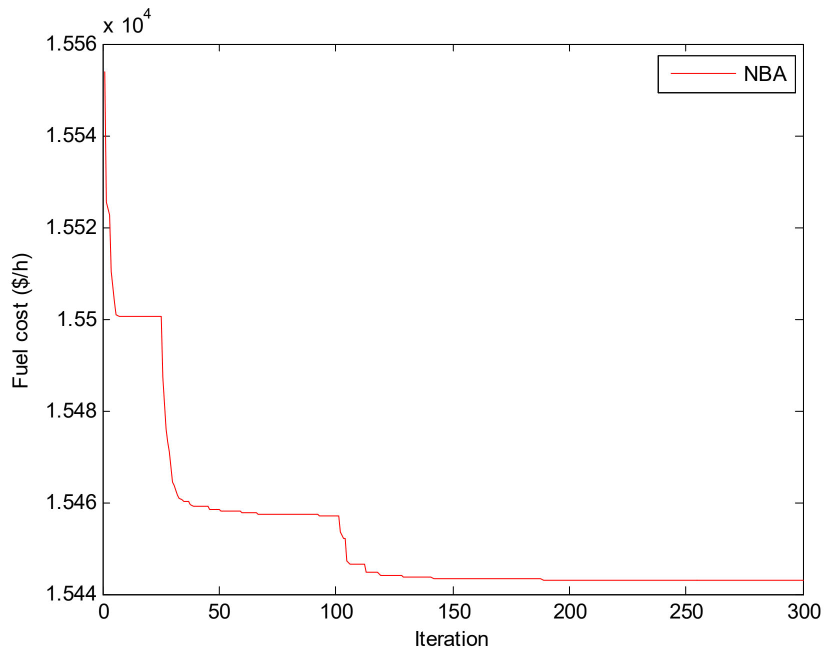

Figure 1 Convergence Characteristics of NBA on Test Case 1

Test Case 2:

The system consists of fifteen thermal generating units and the total load demand of the system is 2630 MW. The parameters of all thermal units are presented in Table 6 [10]. The data of transmission losses (*B* matrices) are taken from [10].

The best fuel cost result obtained from proposed method and other optimization algorithms are compared in Table 7. The generation outputs and corresponding cost obtained by the proposed method are compared with those of GA, PSO, and FA [10, 20]. The proposed algorithm provides a better solution (generation cost of 32,684.4752 $/hr and power losses of 29.1616 (MW)) than other methods while satisfying the system constraints. The convergence characteristic of NBA technique on test case 2 is shown in Figure 2.

The Contribution and Limitations

The significant contributions of this work not only lie in efficiently enhance the performance of BA and shows the proposed algorithm's capability for global optimization, but also depend on the following two aspects. On the one hand, this work creatively proposes a method totally based on the biological basis to improve a specific algorithm. On the other hand, this work successfully incorporates the quantum theory and Doppler effects into Bat Algorithm through further extracting the swarm intelligence from the bats' behaviors.

The major limitation of this work lies in that two parameters that are added to the algorithm may complicate the algorithm. The two parameters are *G* and *CR*, which is the frequency of updating the loudness and pulse emission rate and compensation rate respectively.

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Table 6 Generating Units Capacity and Coefficients (15-Units)

Unit	P_{min} (MW)	P_{max} (MW)	a	b	c	e	f
1	150	455	0.000299	10.1	671	100	0.084
2	150	455	0.000183	10.2	574	100	0.084
3	20	130	0.001126	8.8	374	100	0.084
4	20	130	0.001126	8.8	374	150	0.063
5	150	470	0.000205	10.4	461	120	0.077
6	135	460	0.000301	10.1	630	100	0.084
7	135	465	0.000364	9.8	548	200	0.042
8	60	300	0.000338	11.2	227	200	0.042
9	25	162	0.000807	11.2	173	200	0.042
10	25	160	0.001203	10.7	175	200	0.042
11	20	80	0.003586	10.2	186	200	0.042
12	20	80	0.005513	9.9	230	200	0.042
13	25	85	0.000371	13.1	225	300	0.035
14	15	55	0.001929	12.1	309	300	0.035
15	15	55	0.004447	12.4	323	300	0.035

Table 7 Best Solution of 15-Unit Systems (P_D = 2630 MW)

Unit power output	GA [10]	PSO [10]	FA [20]	BA	NBA
P1 (MW)	415.3108	439.1162	455	410.8874	454.8696
P2 (MW)	359.7206	407.9729	380	455.0000	444.0594
P3 (MW)	104.4250	407.9729	130	130.0000	130.0000
P4 (MW)	74.9853	129.9925	130	130.0000	130.0000
P5 (MW)	380.2844	151.0681	170	246.9576	150.1601
P6 (MW)	426.7902	459.9978	460	458.5244	460.0000
P7 (MW)	341.3164	425.5601	430	328.9262	465.0000
P8 (MW)	124.7876	98.5699	71.7450	60.0801	60.0194
P9 (MW)	133.1445	113.4936	58.9164	25.0086	162.0000
P10 (MW)	89.2567	101.1142	160	160.0000	25.0045
P11 (MW)	60.0572	33.9116	80	80.0000	55.7529
P12 (MW)	49.9998	79.9583	80	80.0000	67.1821
P13 (MW)	38.7713	25.0042	25	25.0396	25.0005
P14 (MW)	41.4140	41.4140	15	55.0000	15.0632
P15 (MW)	22.6445	36.6140	15	15.0167	15.0499
Total power output (MW)	2668.2782	2662.4306	2660.6614	2660.4407	2659.1616
Generation cost ($/h)	33113	32858	32704.4501	32774.0331	32684.4752
Power losses (MW)	38.2782	32.4306	30.6614	30.4407	29.1616

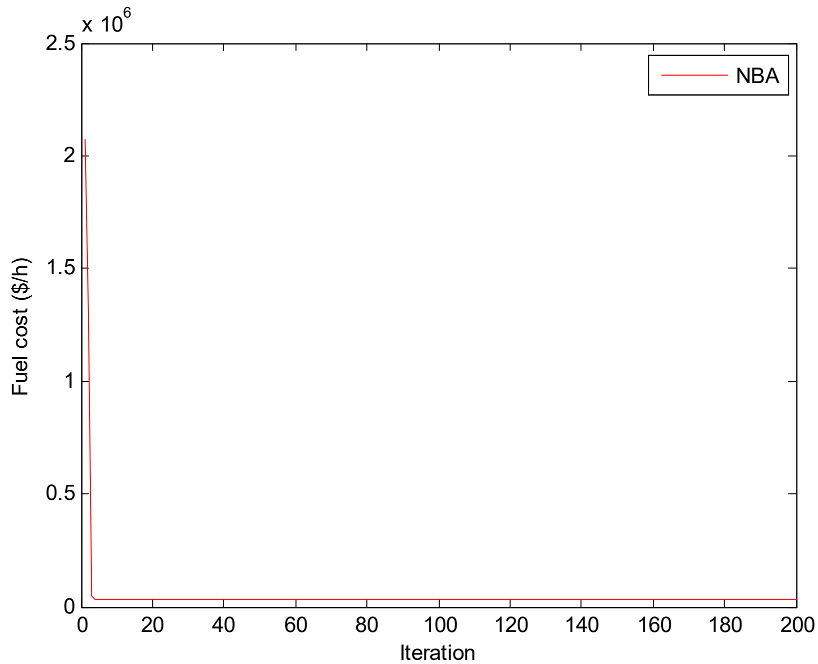

Figure 2 Convergence Characteristics of NBA on Test Case 2

5. CONCLUSION

In this paper, a novel bat algorithm (NBA) technique has been applied to solve the non-convex ELD problem of generating units considering the valve-point effects, prohibited operation zones, ramp rate limits and transmission losses. The proposed technique has provided the global solution in the 6-unit and 15-unit test systems and the better solution than the previous studies reported in literature. The NBA technique has superior features including quality of solution, and stable convergence characteristics for large power systems. Hence, these results suggest that the proposed method is a promising technique for solving complicated problems in power systems. The future work will be explored to incorporate multi-fueling options constraints into the objective function formulation by using the proposed NBA technique.

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