A NOVEL BAT ALGORITHM FOR DYNAMIC ECONOMIC POWER DISPATCH WITH PROHIBITED OPERATING ZONES

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ABSTRACT

This paper proposes a new meta-heuristic search algorithm, called Novel Bat Algorithm (NBA). 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 bat habitats is modeled as an option between quantum behavior and mechanical behavior. The effectiveness and feasibility of the proposed method are demonstrated by two real power systems and compared with other optimization algorithms reported in the literature. Many practical constraints of generators such as ramp rate limits, prohibited operating zones, and transmission losses are considered. The new algorithm is implemented for solving the dynamic economic dispatch (DED) problem so as to minimize the total generation cost when considering the linear and non-linear constraints. In order to validate the proposed algorithm, it is applied to two cases with 6-unit and 15-unit power systems for a 24-hour time interval, respectively. The results show that the proposed algorithm indeed produce a more optimal solution in both cases when compared to the results of other optimization algorithms reported in the literature.

Keywords: *Dynaic economic dispatch, novel bat algorithm, ramp rate limits, prohibited operating zones*

1. INTRODUCTION

In the modern electric power system, there exists a wide range of problems involving optimization processes. Among them, power system scheduling is one of the most important problems in the planning, operation and control. Dynamic economic dispatch (DED) is a more realistic dispatch model than economic dispatch because power systems meet the demand for several intervals. The goal is to determine the optimum power outputs of all the generating units by minimizing the total fuel cost. Additional practical constraints such as lower and upper bounds on the ramp rate limits of units in real power systems are considered in the DED problem, where the generating units will not respond to instantaneous load variations. In addition, considering non-linear characteristics makes the DED problem a non-smooth and non-convex optimization problem. Regarding the DED problem, there were a number of conventional methods that have been applied to handle this problem such as linear programming, dynamic programming, and Lagrangian relaxation [1-3]. Unfortunately, for generating units with non-linear characteristics such as ramp rate limits, prohibited operating zones, and non-convex cost functions, the conventional methods can hardly obtain the optimal solution. The conventional methods often oscillate resulting in minimum local solutions or longer solution times, especially for large-scale power systems that have many generating units. In addition, as new research, a new algorithm called the Brent method was proposed to solve the DED problem and it is applied to determine the optimal lambda [4].

In recent years, computational intelligence techniques have been developed and proposed so as to solve a wide range of power system problems including DED problem. The heuristic optimization methods have been widely used in solving DED problems to obtain global or near-global optimum solutions [5-27]. These methods are good for global searching due to their capability of exploring and finding promising regions in the search space at an advantageous time, and they overcome the main limitations of deterministic techniques, e.g., getting trapped in a local optimum.

In this paper, a new meta-heuristic search algorithm, called Novel Bat Algorithm (NBA), which focuses on further mimicking the bats' behaviors and improving BA in view of biology. The proposed algorithm incorporates the bats' habitat selection and their self-adaptive

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compensation for Doppler effects in echoes into the basic BA. The bats' habitat selection is modeled as the selection between their quantum behaviors and mechanical behaviors. The proposed technique has been used to solve DED problem considering some non-linear characteristics of generators such as the ramp rate limits, prohibited operating zones, and transmission losses. The proposed method is tested for two different test systems and the obtained results are compared with other methods reported in recent literature in order to demonstrate its performance.

2. DED PROBLEM FORMULATION

The main goal 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 [28-36]

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

where $F_{i,t}$ is the fuel cost of the *ith* unit at time interval t in \$/h, a_i, b_i, and c_i are the cost coefficient of *ith* generating unit, $P_{i,t}$ is the real power output of generating unit *ith* at time period t in MW, and N is the number of generators. T is the total number of hours on the operating horizon. 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 [28-38].

$$\sum_{i=1}^{N} P_{i,t} = P_{D,t} + P_{L,t} \quad (2)$$

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 the ***B*** matrix technique and is defined by (3) as [28-30, 32, 34-35, 37-39],

$$P_{L,t} = \sum_{i=1}^{n}\sum_{j=1}^{n} P_{i,t} B_{ij} P_{j,t} + \sum_{i=1}^{n} B_{0i} P_{i,t} + B_{00} \quad (3)$$

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

2.2 Generator Limits

For power balance, an equality constraint should be satisfied. The generation output of each unit should be laid within its lower and upper bounds of generation. The corresponding inequality constraints for each generator are as follows [28, 32-34, 35-37],

$$P_{i,\min} \le P_{i,t} \le P_{i,\max} \quad (4)$$

where $P_{i,\,min}$ and $P_{i,\,max}$ are the minimum and maximum real power output of *i*th unit 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 (5) and (6), respectively [28-31, 33, 37, 39-40].

$$P_{i,t} - P_{i,t-1} \le UR_i \quad (5)$$

$$P_{i,t-1} - P_{i,t} \le DR_i \quad (6)$$

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-ups and ramp-down limits of *i*th unit (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 [28-31, 33, 37-38]:

$$\max\{P_{i,\min}, P_{i,t-1} - DR_i\} \le P_{i,t} \le \min\{P_{i,\max}, P_{i,t-1} + UR_i\} \quad (7)$$

2.4 Prohibited Operating Zones

In practical operation, the entire operating range of a generating unit is not always available due to physical operation limitations. Prohibited operating zones means the unit is prohibited from generation due to some technical fault in the shaft bearings caused by the operation of steam values or related auxiliaries, such as boilers, feed pumps, etc. Such faults may lead to instability in certain ranges of generator power output.

Therefore, the generating units with prohibited operating zones, there are additional constraints on the unit operating range as follows [28-29, 33, 37-40]:

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

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

3. BAT ALGORITHM

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 echolocation behavior in locating their foods. This echolocation characteristic is copied in the virtual Bat algorithm with the following assumptions [21, 32-34, 36, 41-43]:

- All the bats are following the echolocation mechanism, and they could distinguish between prey and obstacle.
- 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.
- 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

The initial population is generated randomly for n number of bats. Each individual of the population consists of real-valued vectors with *d* dimensions [32-34, 44]. The following equation is used to generate the initial population:

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

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 [32-35, 37].

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

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

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

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 on 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 [32-35].

$$x_{new} = x_{old} + \varepsilon A^t \quad (13)$$

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 this time step.

3.3 Loudness and Pulse Emission

As iteration increases, the loudness and pulse emission have to update 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 [32-35, 37]

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

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 [32-34, 37]

$$A_i^t \to 0,\ r_i^t \to r_i^0 \text{ as } t \to \infty \quad (15)$$

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 [32-35, 37].

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 (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

4. THE NOVEL BAT ALGORITHM

In the BA, the Doppler Effect and the idea of the foraging of bats were 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 [34, 43-46], 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.

4.1 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 on them. During the process of search, pursuant to a certain probability of mutation p_m, some bats will be mutated with quantum behavior [45]; these bats are updated with the following formulas:

$$x_{ij}^{t+1} = \begin{cases} g_j^t + \theta * \left|mean_j^t - x_{ij}^t\right| * \ln\left(\dfrac{1}{u_{ij}}\right); & \text{if } rand_j(0,1) < 0.5 \\ g_j^t - \theta * \left|mean_j^t - x_{ij}^t\right| * \ln\left(\dfrac{1}{u_{ij}}\right); & \text{otherwise} \end{cases} \quad (16)$$

4.2 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 $CR \in [0, 1]$ 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 [34, 45]:

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

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

$$v_{ij}^{t+1} = w * v_{ij}^t + (g_j^t - x_{ij}^t) * f_{ij} \quad (19)$$

$$x_{ij}^{t+1} = x_{ij}^t + v_{ij}^t \quad (20)$$

4.3 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 [34, 45]. At time step *t*, the mean loudness of all bats is A^t_{mean} .

$$\text{If} \quad \left(rand(0,1) > r_i\right) \tag{21}$$

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

$$\sigma^2 = \left|A_i^t - A_{mean}^t\right| + \xi \tag{23}$$

The pseudo code of the NBA is presented in Table 2 [34, 41].

Table 2: Pseudo code of NBA.

```
Novel bat algorithm
Objective function f(x), x = (x_1, ..., 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 (16)
        else
        Generate new solution using (17) – (20)
        end if
        if (rand (0, 1) > r_i)
        Generate a local solution around the selected best solution using (21) and (22)
        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
```

5. SIMULATION RESULTS AND DISCUSSIONS

In order to demonstrate the performance of the proposed NBA technique, 6-unit and 15-unit power systems were tested. The generating unit operational constraint, ramp rate limits, prohibited operating zones, and transmission losses are considered. The results obtained from the proposed method were compared in terms of the solution quality and computation efficiency with those reported in the literature. The algorithm was implemented in MATLAB R2010a on a PC with Pentium IV 3.6 GHz processor and 2 GB RAM. The demand of the system has been devided into 24 intervals. The data employed for the 6-unit and 15-unit power systems can be found from [4, 19, 47], as given in Appendix. During normal operation of the system, the loss coefficients B with the 100-MVA base is taken from [4, 47] and B loss coefficients matrix for the sample test systems are given in Appendix.

The parameters of NBA technique used for simulation are: $\alpha = \gamma = 0.9$; $f_{min} = 0$; $f_{max} = 1.5$; $A_0 \in [0, 2]$; $r_0 \in [0, 1]$; $G = 10$; $P \in [0.5, 0.9]$; $w \in [0.4, 0.9]$; $CR \in [0.1, 0.9]$; $\theta \in [0.5, 1]$.

5.1 Case 1: 6-unit system

The system contains 6-unit power system and the details including cost coefficients, generation limits, ramp rate limits, prohibited operating zones, transmission loss coefficients, and forecasted load demand of each interval are presented in the literature [4, 19, 47-49]. The one day scheduling period is divided into 24 intervals. The optimal dispatch of generating units is determined by the proposed NBA technique. The minimum and maximum operating limit of each generating unit is obtained by enforcing the ramp down and ramp up limits of generating unit with the real power dispatch of previous interval. Total power capacities were committed to meet the 24-hour load demands from 930 MW to 1263 MW that was shown in Table C (Appendix). The optimal dispatches of the entire scheduling period are presented in Table 3. Total fuel cost and power losses by NBA are \$313343.4523 and 217.9019 MW, respectively. The obtained results of the proposed method are compared by the FEP, IFEP, PSO, and hybrid HNN from [21] in terms generation cost and computational time as shown in Table 6. From the comparison, it is clear that the proposed methodology provides an improvement in the total annual cost savings of \$ 85974.9105 compared with hybrid HNN.

Table 3: Hourly generation schedule, cost and power losses by NBA for 6-unit system

H	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	P6 (MW)	Cost ($)	Ploss (MW)
1	383.7123	124.6102	206.6102	86.8062	110.4463	50.0000	11419.3331	7.1852
2	380.4708	122.2344	204.2085	84.1072	107.9777	50.0000	11256.6052	6.9986
3	378.7429	120.9508	202.8979	82.6789	106.6280	50.0000	11169.2393	6.8986
4	377.5093	120.0479	201.9613	81.6439	105.6655	50.0000	11106.9451	6.8278
5	378.7439	120.9572	202.8967	82.6709	106.6299	50.0000	11169.2393	6.8987
6	385.6544	126.0594	208.1520	88.4087	112.0291	50.0000	11519.7817	7.3036
7	392.0712	130.8085	213.0208	93.7666	117.0231	50.0000	11847.8631	7.6902
8	400.2776	136.8515	219.2381	100.5887	123.4072	50.8382	12280.6356	8.2013
9	421.5039	152.4957	235.4294	118.4381	139.8709	67.9310	13614.0612	9.6689
10	426.4597	156.1484	239.2078	122.6117	143.7046	71.9052	13929.4373	10.0375
11	436.9981	163.9173	247.2532	131.5047	151.8355	80.3449	14605.4961	10.8537
12	444.0395	169.1051	252.6119	137.4434	157.2677	85.9555	15060.6566	11.4231
13	434.7309	162.2342	245.5145	129.5783	150.0934	78.5226	14459.0018	10.6741
14	447.3626	171.5406	255.1306	140.2296	159.8122	88.6223	15276.0850	11.6979
15	449.8404	173.3807	257.0338	142.3449	161.7323	90.5751	15438.1757	11.9070
16	447.1466	171.3952	254.9799	140.0691	159.6605	88.4293	15262.5975	11.6807
17	441.1407	166.9684	250.4019	134.9955	155.0344	83.6453	14872.8055	11.1862
18	437.2089	164.0706	247.4046	131.6770	152.0035	80.5056	14618.8323	10.8702
19	428.3186	157.5181	240.6271	124.1788	145.1408	73.3949	14048.1599	10.1782
20	414.4898	147.3255	230.0802	112.5345	134.4384	62.2955	13170.3067	9.1640
21	400.2782	136.8522	219.2379	100.5872	123.4075	50.8383	12280.6356	8.2013
22	390.8524	129.8952	212.0811	92.7307	116.0555	50.0000	11784.5776	7.6150
23	388.6209	128.2525	210.3926	90.8796	114.3350	50.0000	11670.8952	7.4806
24	384.9161	125.5162	207.5816	87.7989	111.4466	50.0000	11482.0859	7.2594
Total							**313343.4523**	**217.9019**

Table 4: Hourly generation (MW) schedule by NBA for 15-unit system

H	P1	P2	P3	P4	P5	P6	P7	P8
1	382.792	293.264	130.000	130.000	150.175	450.108	464.999	60.049
2	378.697	285.011	130.000	130.000	150.097	442.825	465.000	60.001
3	380.816	289.403	130.000	130.000	150.002	447.436	465.000	60.001
4	381.583	294.878	130.000	130.000	150.001	449.781	464.999	60.020
5	405.092	319.439	129.999	130.000	150.060	460.000	465.000	60.001
6	408.859	332.900	130.000	130.000	150.008	459.997	465.000	60.000
7	415.614	340.372	130.000	130.000	150.006	459.970	465.000	60.000
8	454.988	402.010	130.000	130.000	150.395	460.000	465.000	60.045
9	455.000	454.981	130.000	130.000	305.518	459.999	464.992	60.037
10	454.887	455.000	130.000	129.891	329.857	459.975	464.988	61.543
11	455.000	455.000	130.000	129.948	365.542	460.000	464.999	62.359
12	454.889	454.997	130.000	129.981	340.902	460.000	464.997	62.531
13	455.000	454.999	129.965	129.979	333.302	459.992	464.999	60.003
14	454.999	455.000	129.984	130.000	390.699	460.000	464.998	60.157
15	454.993	454.979	129.892	129.999	470.000	450.901	465.000	60.252
16	455.000	455.000	130.000	130.000	468.960	460.000	465.000	60.578
17	454.991	455.000	130.000	130.000	411.030	460.000	464.997	65.905
18	454.997	454.915	130.000	130.000	363.568	459.921	465.000	61.183
19	455.000	454.999	129.983	130.000	266.999	459.999	465.000	61.845
20	454.999	454.950	130.000	130.000	198.764	460.000	465.000	60.000
21	454.999	416.086	130.000	130.000	150.572	460.000	465.000	60.629
22	407.062	331.008	130.000	130.000	150.001	460.000	465.000	60.003
23	385.943	306.610	130.000	130.000	150.028	459.170	465.000	60.003
24	387.160	300.490	130.000	130.000	150.004	456.348	465.000	60.002

Table 4: Hourly generation (MW) schedule by NBA for 15-unit system (Cont.)

H	P9	P10	P11	P12	P13	P14	P15	
1	25.010	25.029	37.093	51.377	25.000	15.010	15.064	
2	25.000	25.000	36.178	50.835	25.000	15.016	15.000	
3	25.000	25.000	36.258	50.911	25.000	15.000	15.000	
4	25.000	25.093	36.813	51.801	25.000	15.001	15.000	
5	25.005	25.000	39.452	53.873	25.006	15.017	15.001	
6	25.001	25.000	40.153	54.351	25.002	15.000	15.000	
7	25.025	25.000	40.620	54.931	25.003	15.000	15.001	
8	25.126	25.049	47.290	60.735	25.000	15.000	15.032	
9	25.678	26.410	41.244	71.515	25.041	15.023	15.028	
10	27.338	39.055	70.952	80.000	25.293	15.014	15.462	
11	25.000	51.569	78.012	80.000	25.030	18.917	15.235	
12	25.023	91.911	68.442	78.785	25.003	15.164	15.421	
13	25.360	85.135	75.899	79.983	27.346	15.385	15.056	
14	42.069	49.413	78.417	79.975	25.013	19.752	25.274	
15	26.058	128.581	79.945	79.956	25.001	15.180	16.281	
16	27.572	124.031	79.999	79.661	26.690	15.000	15.321	
17	45.400	102.564	80.000	80.000	25.317	20.565	15.001	
18	25.229	76.355	79.925	80.000	25.088	15.176	15.595	
19	25.017	26.621	67.777	80.000	25.051	15.673	15.049	
20	25.086	27.152	69.078	79.408	25.003	15.006	15.001	
21	25.035	25.034	20.543	61.987	25.003	15.106	15.000	
22	25.001	25.000	39.958	54.169	25.000	15.000	15.001	
23	25.000	25.001	37.569	51.031	25.005	15.002	15.000	
24	25.000	25.000	37.140	52.092	25.002	15.000	15.000	

Table 5: Hourly production cost ($) and power losses (MW) by NBA for 15-unit system

H	Cost	Ploss	H	Cost	Ploss	H	Cost	Ploss	H	Cost	Ploss
1	28359.3027	18.9686	7	29357.8293	20.5420	13	34208.4628	32.4026	19	32780.5295	28.0126
2	28138.7673	18.6647	8	30541.0065	22.6674	14	34794.1648	35.7489	20	32047.9616	25.4471
3	28254.1042	18.8265	9	32789.9822	29.4663	15	36162.9596	43.0172	21	30428.8932	22.9928
4	28359.1000	18.9697	10	33630.6064	31.2547	16	36130.2089	42.8116	22	29157.7183	20.2023
5	29010.4656	19.9445	11	34244.0108	33.6119	17	35591.5844	38.7695	23	28621.5382	19.3620
6	29199.8284	20.2717	12	34264.6681	33.0450	18	34460.6638	33.9519	24	28547.9966	19.2370

Table 6 Comparison of best costs and computing time for two test systems

Method	Total generation cost ($)		Computing time (s)	
	6-units	15-units	6-units	15-units
FEP [21]	315634	796642	357.58	362.63
IFEP [21]	315993	794832	546.06	574.85
PSO [21]	314782	774131	2.27	3.31
Hybrid HNN [21]	313579	759796	1.52	2.22
NBA	313343.4523	759082.3530	1.02	1.84

5.2 Case 2: 15-unit system

The cost coefficients, maximum and minimum generation limits, ramp rate limits, prohibited operating zones, load demand for each interval, and the transmission loss coefficients are presented in the literature [4,19,47-50]. The one-day scheduling period is considered and the scheduling period is divided into 24 equal intervals. The minimum and maximum load demands of the scheduling period are 2226 and 2970 MW that was shown in Table G (Appendix). The hourly generation schedule by the proposed technique for 15-unit systems is presented in Table 4. The hourly production cost ($) and power losses (MW) by NBA for 15-unit systems are presented in Table 5. Total fuel cost and power losses by NBA are $ 759082.3530 and 648.1884 MW, respectively. The obtained results of the proposed method are compared by the FEP, IFEP, PSO, and hybrid HNN from [21] in terms generation cost and computational time as shown in Table 6. The comparison clearly indicates that the proposed methodology provides a better schedule than recent reports.

And also, it is clear that the proposed methodology provides an improvement in the total annual cost savings of $ 260481.155 compared with hybrid HNN.

6. CONCLUSION

In this paper, a Novel Bat Algorithm (NBA) has been successfully applied to solve DED problem of generating units considering the ramp rate limits, prohibited operating zones, and transmission losses. The proposed technique incorporates the bat's habitat selection and their self-adaptive compensation for Doppler effects in echoes into the basic BA and designs a new local strategy. The effectiveness of the proposed method is illustrated by using a 6-unit and 15-unit power system. The proposed technique has provided results comparable to or better than those produced by other algorithms reported in the literature and the solution obtained has superior solution quality in terms of minimum production cost and computation time. From this limited comparative study, it can be concluded that the proposed NBA technique can be effectively used to solve DED problems. 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. First aspect, this work creatively proposes a method totally based on the biological basis to improve a specific algorithm. Second aspect, this work successfully incorporates the quantum theory and Doppler effects into BA through further extracting the swarm intelligence from the bats' behaviors.

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Appendix

Table A: Generating unit capacity and coefficients (6-unit system)

Unit	$P_{i,\min}$ (MW)	$P_{i,\max}$ (MW)	a_i (\$/MW^2)	b_i (\$/MW)	c_i (\$)
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 B: Ramp-rate limits and prohibited operating zones (6-unit system)

Unit	P_i^0	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]

Table C: Load demand for 24 hours (6-unit system)

Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)
1	955	7	989	13	1190	19	1159
2	942	8	1023	14	1251	20	1092
3	935	9	1126	15	1263	21	1023
4	930	10	1150	16	1250	22	984
5	935	11	1201	17	1221	23	975
6	963	12	1235	18	1202	24	960

Table D: Transmission loss coefficients (6-unit system)

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

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

$$B_{00} = 0.0056$$

Table E: Generating unit data (15-unit system)

Unit	$P_{i,\min}$ (MW)	$P_{i,\max}$ (MW)	a_i (\$/MW^2)	b_i (\$/MW)	c_i (\$)	UR_i (MW/h)	DR_i (MW/h)	P_i^0
1	150	455	0.000299	10.1	671	80	120	400
2	150	455	0.000183	10.2	574	80	120	360
3	20	130	0.001126	8.8	374	130	130	105
4	20	130	0.001126	8.8	374	130	130	100
5	150	470	0.000205	10.4	461	80	120	190
6	135	460	0.000301	10.1	630	80	120	400
7	135	465	0.000364	9.8	548	80	120	350
8	60	300	0.000338	11.2	227	65	100	95
9	25	162	0.000807	11.2	173	60	100	105
10	25	160	0.001203	10.7	175	60	100	110
11	20	80	0.003586	10.2	186	80	80	60
12	20	80	0.005513	9.9	230	80	80	40
13	25	85	0.000371	13.1	225	80	80	30
14	15	55	0.001929	12.1	309	55	55	20
15	15	55	0.004447	12.4	323	55	55	20

Table F: Prohibited operating zones (15-unit system)

Unit	Prohibited operating zones (MW)
2	[185 – 225] [305 – 335] [420 – 450]
5	[180 – 200] [305 – 335] [390 – 420]
6	[230 – 255] [365 – 395] [430 – 455]
12	[30 – 40] [55 – 65]

Table G: Load demand for 24 hours (15-unit system)

Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)
1	2236	7	2331	13	2780	19	2651
2	2215	8	2443	14	2830	20	2584
3	2226	9	2651	15	2953	21	2432
4	2236	10	2728	16	2950	22	2312
5	2298	11	2783	17	2902	23	2261
6	2316	12	2785	18	2803	24	2254