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Multi-Objective Emission Constrained Economic Power Dispatch Using Novel Bat Algorithm

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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 bats' habitat is modeled as the selection between their quantum behaviors and mechanical behaviors. The new algorithm is implemented to solve Environmental/Economic power Dispatch (EED) problem in power systems considering the power limits, valve-point effects and transmission loss. The EED problem can be solved by summing up the minimization of generation cost and emission by considering weighting factor. The effectiveness of the proposed algorithm has been tested on 10-unit system and the results were compared with other methods reported in recent literature.
Keywords *- Novel bat algorithm, economic dispatch, emission dispatch, environmental economic dispatch, valve-point effects.*

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I. INTRODUCTION

Modern power systems are very complex and include nonlinear characteristics. The economic dispatch (ED) is one of the essential functions in power system operation and control for allocating generation among the committed units which will minimize the generation cost while meeting demand and satisfying equality and inequality constraints. This makes the ED problem a large-scale highly nonlinear constrained optimization problem. Therefore, recently most of the researchers made studies for finding the most suitable power values produced by the generators depending on fuel costs [1, 2]. In these studies, they produced successful results by using various optimization algorithms. Despite the fact that the traditional ED can optimize generator fuel costs, it still cannot produce a solution for environmental pollution due to the excessive emission of fossil fuels [3-5].

Currently, a large part of energy production is done with thermal sources. Thermal power plant is one of the most important sources of carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) which create atmospheric pollution [6]. Emission control has received increasing attention owing to increased concern over environmental pollution caused by fossil based generating units and the enforcement of environmental regulations in recent years [7]. Numerous studies have emphasized the importance of controlling pollution in electrical power systems [8].

Environmental economic dispatch (EED) problem has two objectives consisting of minimum fuel cost and minimum emission. A number of methods have been presented to solve EED problems such as simplified recursive method [9], genetic algorithm [10-12], simulated annealing [13, 14], biogeography based optimization [15], differential evolution [16], artificial bee colony algorithm [17, 18], and particle swarm optimization [19, 20].

In this paper, a new meta-heuristic search algorithm, called Novel Bat Algorithm (NBA) has been used to solve EED problem considering valve-point effects and transmission loss. Feasibility of the proposed method has been demonstrated on 10-unit system. The results obtained with the proposed method were analyzed and compared with other optimization results reported in literature.

II. PROBLEM FORMULATION

The multi-objective environmental economic dispatch can be formulated as follows [11]:

$$F_T = Min\ f(FC, EC) \tag{1}$$

where F_T is the total generation cost of the system, FC is the total fuel cost of generators and EC is the total emission of generators.

2.1. Minimization of Fuel Cost

Total fuel cost of a power generating station including the valve-point effects can be expressed as [11]:

$$FC = \sum_{i=1}^{n} \left(a_i P_i^2 + b_i P_i + c_i + \left| e_i \times \sin\left(f_i \times \left(P_i^{\min} - P_i \right) \right) \right| \right) \tag{2}$$

where P_i is the power generation of the ith unit; a_i, b_i, c_i, e_i, and f_i are fuel cost coefficients of the ith generating unit; and N is the number of generating units.

2.2. Minimization of Emission

The classical ED problem can be obtained by the amount of active power to be generated by the generating units at minimum fuel cost, but it is not considered as the amount of emissions released from the burning of fossil fuels. Total amount of emissions such as SO_2 or NO_X depends on the amount of power generated by until and it can be defined as the sum of quadratic and exponential functions and can be stated as [11]:

$$EC = \sum_{i=1}^{N} \left(\alpha_i P_i^2 + \beta_i P_i + \gamma_i + \eta_i \exp(\delta_i P_i) \right) \tag{3}$$

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

2.3. Environmental Economic Dispatch (EED)

The EED problem can be formulated by using generation cost and amount of emission and converting them into the single optimization problem as shown in equation (4):

$$F_T = (w_1 * FC + w_2 * h * EC) \tag{4}$$

under the following condition,

$$w_1 + w_2 = 1 \ \text{ and } \ w_1, w_2 \geq 0 \tag{5}$$

where w_1, w_2 are weight factor and h is the price penalty factor.

2.4. Problem Constraints

There are two constraints in the EED problem which are power balance constraint and maximum and minimum limits of power generation output constraint.

Power balance constraint:

$$\sum_{i=1}^{N} P_i = P_D + P_L \tag{6}$$

$$P_L = \sum_{i}^{N} \sum_{j}^{N} B_{ij} P_i P_j \tag{7}$$

Generating capacity constraint:

$$P_{i\min} \leq P_i \leq P_{i\max} \tag{8}$$

where P_D is total demand of system (MW); P_L is total power loss; $P_{i\ min}$ and $P_{i\ max}$ are minimum and maximum generation of unit i (MW); and B_{ij} is coefficients of transmission loss.

III. META-HEURISTIC OPTIMIZATION

3.1. 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, 22]:

- 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 ∈ [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}.

3.1.1 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 [23]. 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.

3.1.2 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 β ∈ [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.

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

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

3.1.3 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

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

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

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

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 (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

3.2. The 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.

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:

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

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]:

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

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

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

$$x_{ij}^{t+1} = x_{ij}^t + v_{ij}^t \tag{20}$$

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^t_{mean} .

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

$$x^{t+1}_{ij} = g^t_j * (1 + rand\ n(0,\sigma^2)) \tag{22}$$

$$\sigma^2 = \left|A^t_i - A^t_{mean}\right| + \xi \tag{23}$$

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, ..., 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
```

IV. SIMULATION RESULTS

The proposed method is tested on 10-unit system with considering power limits, valve-point effects and transmission loss. Total load demand of the power system is 2000 MW. The generator cost coefficients, emission coefficients and transmission loss coefficients for ten unit system are taken from [25] and given in appendix. Simulations were performed in MATLAB R2010a environment on a PC with a 3 GHz processor. The parameters of NBA technique used for simulation are: $\alpha = \gamma = 0.9$; $f_{min} = 0$; $f_{max} = 1.5$; $A_0 \in [0, 2]$; $r_0 \in [0, 1]$; $G = 10$; $P \in [0.5, 0.9]$; $w \in [0.4, 0.9]$; $CR \in [0.1, 0.9]$; $\theta \in [0.5, 1]$.

In the simulation, three scenarios are considered:

- scenario 1: minimization of fuel cost (w_1=1, w_2=0)
- scenario 2: minimization of emission (w_1=0, w_2=1)
- scenario 3: minimization of fuel cost and emission (w_1=0.5, w_2=0.5)

For the first scenario, the total fuel cost optimzed using the proposed method is 111492.3925 \$/h. The corresponding total emission and total power loss are 4569.2173 lb/h and 87.0307 MW respectively. The best results of the proposed method for fuel cost minimization compared with other methods are illustrated in Table 3. In the second scenario, the total emission is optimed individually, the best value found is 3832.3793 lb/h. The corresponding total fuel cost and total power loss achieved are 116320.1323 \$/h and 81.4940 MW respectively. Detail results of the proposed method for emission minimization compared with other methods are illustrated in Table 4.

Table 3: Comparison of the best fuel cost results of each method (P_D = 2000 MW)

Unit Output	ABC_PSO [22]	DE [16]	SA [14]	**NBA**
P1 (MW)	55	55	54.9999	54.9951
P2 (MW)	80	79.89	80	79.9998
P3 (MW)	106.93	106.8253	107.6263	106.2766
P4 (MW)	100.5668	102.8307	102.5948	100.6469
P5 (MW)	81.49	82.2418	80.7015	80.7678
P6 (MW)	83.011	80.4352	81.1210	84.3447
P7 (MW)	300	300	300	300.0000
P8 (MW)	340	340	340	340.0000
P9 (MW)	470	470	470	469.9999
P10 (MW)	470	469.8975	470	470.0000
Losses (MW)	87.0344	-	87.0434	87.0307
Fuel cost ($/h)	111500	111500	111498.6581	111492.3925
Emission (lb/h)	4571.2	4581	4584.8366	4569.2173

In the third scenario, the two objectives functions are optimized simultaneously (the fuel cost and emission). The best results of combined environmental economic dispatch when the objective function is minimized both fuel cost and emission are presented in Table 5. The total fuel cost and total emission are 113409.8128 $/h and 4117.2719 lb/h respectively. The corresponding total power loss is 83.7009 MW. Figure 1 shows the bar chart of fuel cost and emission with the proposed method for the three scenarios.

Table 4: Comparison of the best emission results of each method (P_D = 2000 MW)

Unit Output	ABC_PSO [22]	DE [16]	SA [14]	**NBA**
P1 (MW)	55	55	54.9999	55.0000
P2 (MW)	80	80	80	79.9762
P3 (MW)	81.9604	80.5924	76.6331	80.7793
P4 (MW)	78.8216	81.0233	79.4332	80.5684
P5 (MW)	160	160	160	159.9971
P6 (MW)	240	240	240	240.0000
P7 (MW)	300	292.7434	287.9285	294.2561
P8 (MW)	292.78	299.1214	301.4146	299.5728
P9 (MW)	401.8478	394.5147	412.4386	397.7499
P10 (MW)	391.2096	398.6383	388.9348	393.5942
Losses (MW)	81.5879	-	81.7827	81.4940
Fuel cost ($/h)	116420	116400	116386	116320.1323
Emission (lb/h)	3932.3	3923.4	3935.9769	3832.3793

Table 5: Comparison of EED results of each method (P_D = 2000 MW)

Unit Output	ABC_PSO [22]	DE [16]	NSGA-II [16]	**NBA**
P1 (MW)	55	54.9487	51.9515	55.0000
P2 (MW)	80	74.5821	67.2584	79.9920
P3 (MW)	81.14	79.4294	73.6879	86.5561
P4 (MW)	84.216	80.6875	91.3554	83.2342
P5 (MW)	138.3377	136.8551	134.0522	142.6408
P6 (MW)	167.5086	172.6393	174.9504	160.3452
P7 (MW)	296.8338	283.8233	289.435	298.3290
P8 (MW)	311.5824	316.3407	314.0556	323.9501
P9 (MW)	420.3363	448.5923	455.6978	426.4291
P10 (MW)	449.1598	436.4287	431.8054	427.2244
Losses (MW)	84.1736	-	-	83.7009
Fuel cost ($/h)	113420	113480	113540	113409.8128
Emission (lb/h)	4120.1	4124.9	4130.2	4117.2719

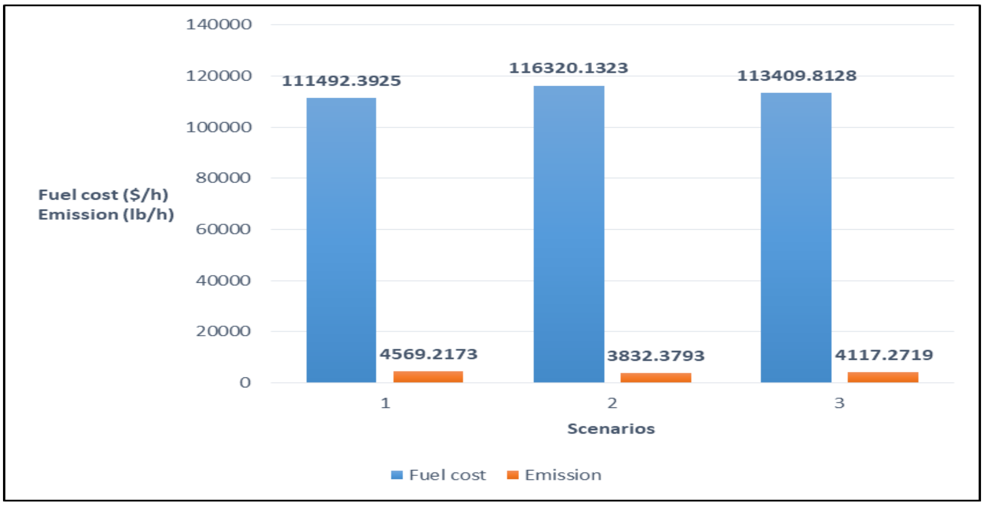

Figure 1. Fuel cost and emission with proposed method for the three scenarios

V. CONCLUSION

In this paper, a Novel Bat Algorithm (NBA) has been successfully applied to solve EED problem of generating units considering the valve-point effects 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 Bat Algorithm (BA) and design a new local strategy. The proposed technique has provided results comparable to or better than those produced by other algorithms and the solution obtained have superior solution quality. The obtained results for three scenarios was always comparable or better solution than the previous studies reported in literature. From this limited comparative study, it can be concluded that NBA technique can be effectively used to solve EED problems.

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APPENDIX

Table A: Generating unit capacity and fuel cost coefficients [16]

Generating unit	$P_{i,min}$ (MW)	$P_{i,max}$ (MW)	a_i ($/MW^{2}h)	b_i ($/MWh)	c_i ($/h)	e_i ($/h)	f_i (rad/MW)
1	10	55	0.12951	40.5407	1000.403	33	0.0174
2	20	80	0.10908	39.5804	950.606	25	0.0178
3	47	120	0.12511	36.5104	900.705	32	0.0162
4	20	130	0.12111	39.5104	800.705	30	0.0168
5	50	160	0.15247	38.5390	756.799	30	0.0148
6	70	240	0.10587	46.1592	451.325	20	0.0163
7	60	300	0.03546	38.3055	1243.531	20	0.0152
8	70	340	0.02803	40.3965	1049.998	30	0.0128
9	135	470	0.02111	36.3278	1658.569	60	0.0136
10	150	470	0.01799	38.2704	1356.659	40	0.0141

Table B: Emission coefficients [16]

Generating unit	α_i (lb/MW^{2}h)	β_i (lb/MWh)	γ_i (lb/h)	η_i (lb/h)	δ_i (1/MW)
1	0.04702	-3.9864	360.0012	0.25475	0.01234
2	0.04652	-3.9524	350.0012	0.25475	0.01234
3	0.04652	-3.9023	330.0056	0.25163	0.01215
4	0.04652	-3.9023	330.0056	0.25163	0.01215
5	0.00420	0.3277	13.8593	0.24970	0.01200
6	0.00420	0.3277	13.8593	0.24970	0.01200
7	0.00680	-0.5455	40.2699	0.24800	0.01290
8	0.00680	-0.5455	40.2699	0.24990	0.01203
9	0.00460	-0.5112	42.8955	0.25470	0.01234
10	0.00460	-0.5112	42.8955	0.25470	0.01234

Table C: Transmission loss coefficients of 10-unit system [16]

$$B_{ij} = 10^{-5} \times \begin{bmatrix} 4.9 & 1.4 & 1.5 & 1.5 & 1.6 & 1.7 & 1.7 & 1.8 & 1.9 & 2.0 \\ 1.4 & 4.5 & 1.6 & 1.6 & 1.7 & 1.5 & 1.5 & 1.6 & 1.8 & 1.8 \\ 1.5 & 1.6 & 3.9 & 1.0 & 1.2 & 1.2 & 1.4 & 1.4 & 1.6 & 1.6 \\ 1.5 & 1.6 & 1.0 & 4.0 & 1.4 & 1.0 & 1.1 & 1.2 & 1.4 & 1.5 \\ 1.6 & 1.7 & 1.2 & 1.4 & 3.5 & 1.1 & 1.3 & 1.3 & 1.5 & 1.6 \\ 1.7 & 1.5 & 1.2 & 1.0 & 1.1 & 3.6 & 1.2 & 1.2 & 1.4 & 1.5 \\ 1.7 & 1.5 & 1.4 & 1.1 & 1.3 & 1.2 & 3.8 & 1.6 & 1.6 & 1.8 \\ 1.8 & 1.6 & 1.4 & 1.2 & 1.3 & 1.2 & 1.6 & 4.0 & 1.5 & 1.6 \\ 1.9 & 1.8 & 1.6 & 1.4 & 1.5 & 1.4 & 1.6 & 1.5 & 4.2 & 1.9 \\ 2.0 & 1.8 & 1.6 & 1.5 & 1.6 & 1.5 & 1.8 & 1.6 & 1.9 & 4.4 \end{bmatrix}$$

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