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Environmental/Economic Power Dispatch of Thermal Units Using Bat Algorithm

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--*ABSTRACT*--
This paper proposes a new meta-heuristic search algorithm, called Bat Algorithm (BA). Bat algorithm is an optimization technique motivated by the echolocation behavior of natural bats in finding their foods. The 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-generator system and the results were compared with other methods reported in recent literature.
KEYWORDS *- Economic dispatch, emission dispatch, environmental economic dispatch, bat algorithm, valve-point effects.*

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I. INTRODUCTION

The economic dispatch (ED) is one of the important problems in power system operation and control for allocating generation among the committed units. The objective of ED problem of electric power generation is to schedule the committed generating unit outputs so as to meet the load demand at minimum operating cost while satisfying all unit and system 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].

Recently, a new meta-heuristic search algorithm, called Bat Algorithm (BA) [21], has been developed by Yang. In this paper, BA has been used to solve EED problem considering valve-point effects and transmission loss. Feasibility of the proposed method has been demonstrated on ten generator system. The results obtained with the proposed method were analyzed and compared with other optimization results reported in literature.

II. PROBLEM FORMULATION

The EED problem consists of two objective functions, which are economic and emission dispatches. Then these two functions are combined to solve the problem. The EED problem can be formulated as follows [11]:

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

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

The fuel cost of each generating unit, considering the valve-point effects, is defined as the sum of a quadratic function and a sinusoidal function [11]. Total fuel cost of a power generating station can be expressed as:

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

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. BAT ALGORITHM (BA)

Bat's 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]:

✓ 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. Initialization of Bat Algorithm

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

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

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.

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

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

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

where 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.

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

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.

3.3. 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

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

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

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

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

IV. SIMULATION RESULTS

The proposed techniques have been applied to a test power system consists of ten generators at 2000 MW power demand. Generation unit data has been taken from [22]. Simulations were performed in MATLAB R2010a environment on a PC with a 3 GHz processor. The parameters of algorithm used for simulation are: max generation = 100; population size = 20; A = 0.9; r = 0.1; $f_{min} = 0$ and $f_{max} = 2$.

4.1. Case I: Optimization of each of the two objectives individually.

In this case, the fuel cost and the gas emission are minimized separately as a single objective functions. Minimizing each objective function individually is executed by giving full weight to the function to be optimized and neglecting others. Table 2 presents the results of economic dispatch when the objective is minimizing just the fuel cost (w_1=1, w_2=0). The fuel cost and the gas emission output of 10 unit system for 2000 MW are 111289.3362 $/h and 4405.8689 lb/h respectively when the fuel cost is the optimized function. The power losses are 87.0079 MW.

Table 3, presents the results of economic emission dispatch when the objective is minimizing just the gas emission (w_1=0, w_2=1). The fuel cost and the gas emission output of 10 unit system for 2000 MW are 116263.7831 $/h and 3840.8472 lb/h respectively when the gas emission is the optimized function. The power losses are 81.4492 MW.

Table 2: Comparison of the best fuel cost results of each methods (P_D = 2000 MW)

Unit Output	ABC_PSO [22]	DE [16]	SA [14]	BA
P1 (MW)	55	55	54.9999	55.0000
P2 (MW)	80	79.89	80	79.9885
P3 (MW)	106.93	106.8253	107.6263	101.1444
P4 (MW)	100.5668	102.8307	102.5948	112.6896
P5 (MW)	81.49	82.2418	80.7015	79.8951
P6 (MW)	83.011	80.4352	81.1210	78.2924
P7 (MW)	300	300	300	299.9980
P8 (MW)	340	340	340	339.9999
P9 (MW)	470	470	470	469.9999
P10 (MW)	470	469.8975	470	470.0000
Losses (MW)	87.0344	-	87.0434	87.0079
Fuel cost ($/h)	111500	111500	111498.6581	111289.3362
Emission (lb/h)	4571.2	4581	4584.8366	4405.8689

4.2. Case II: Optimization of the fuel cost and gas emission simultaneously.

In this case, the problem as multi-objective; two objectives are minimized simultaneously (the fuel cost and the gas emission objectives) by using the weighted factors w_1 = 0.5 and w_2 = 0.5. The multi-objective optimization problem can be converted to a single objective optimization problem by introducing weighted factors. Table 4, presents the results of combined environmental economic dispatch when the objective is minimizing both fuel cost and the gas emission. The fuel cost and the gas emission output of 10 unit system for 2000 MW are 113409.8128 $/h and 4117.2719 lb/h respectively. The power losses are 83.7851 MW.

Table 3: Comparison of the best emission results of each methods (P_D = 2000 MW)

Unit Output	ABC_PSO [22]	DE [16]	SA [14]	BA
P1 (MW)	55	55	54.9999	55.0000
P2 (MW)	80	80	80	77.1120
P3 (MW)	81.9604	80.5924	76.6331	80.9084
P4 (MW)	78.8216	81.0233	79.4332	88.7195
P5 (MW)	160	160	160	160.0000
P6 (MW)	240	240	240	240.0000
P7 (MW)	300	292.7434	287.9285	295.6500
P8 (MW)	292.78	299.1214	301.4146	294.6069

P9 (MW)	401.8478	394.5147	412.4386	389.9454
P10 (MW)	391.2096	398.6383	388.9348	399.5071
Losses (MW)	81.5879	-	81.7827	81.4492
Fuel cost ($/h)	116420	116400	116386	116263.7831
Emission (lb/h)	3932.3	3923.4	3935.9769	3840.8472

Table 4: Comparison of EED results of each methods (P_D = 2000 MW)

Unit Output	ABC_PSO [22]	DE [16]	NSGA-II [16]	BA
P1 (MW)	55	54.9487	51.9515	55.0000
P2 (MW)	80	74.5821	67.2584	79.9716
P3 (MW)	81.14	79.4294	73.6879	86.5561
P4 (MW)	84.216	80.6875	91.3554	83.4382
P5 (MW)	138.3377	136.8551	134.0522	142.6408
P6 (MW)	167.5086	172.6393	174.9504	160.3467
P7 (MW)	296.8338	283.8233	289.435	298.3295
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	427.1231
Losses (MW)	84.1736	-	-	83.7851
Fuel cost ($/h)	113420	113480	113540	113409.8128
Emission (lb/h)	4120.1	4124.9	4130.2	4117.2719

V. CONCLUSION

In this paper, Bat Algorithm has been applied to solve EED problem of generating units considering the valve-point effects and transmission losses. The proposed technique has provided the global solution in the 10-generator system and the better solution than the previous studies reported in literature. Also, the equality and inequality constraints treatment methods have always provided the solutions satisfying the constraints.

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