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Woodpecker Mating Algorithm for Optimal Economic Load Dispatch in a Power System with Conventional Generators

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ABSTRACT

Economic Dispatch (ED) is one of the most important optimization problems in power systems. The ultimate goal of ED is to minimize the cost of power generation operations. In this paper, the Woodpecker Mating Algorithm (WMA) is used to solve the ED problem considering the nonlinear properties of generators such as valve point effects (VPE), prohibited operating zones (POZ), ramp rate limits, multiple fuel options, and transmission loss. The WMA algorithm is a novel metaheuristic algorithm inspired by the mating behavior of woodpeckers and sound intensity (a physical quantity). The WMA is implemented on six test systems of different operational dimensions and characteristics to show its capacity for solving the ED problem. The results are compared with the latest and most efficient methods introduced in the literature. Proving the efficiency of the WMA to solve the ED problem, simulation results are promising and offer the optimal fuel cost of production.

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Economic Dispatch, Nonlinear Optimization, Valve Point Effects, Woodpecker Mating Algorithm.

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I. INTRODUCTION

Today, with the increasing demand for electricity, we are facing an increase in the price of fuel produced. Therefore, it is essential to bring down power production costs and develop a reliable operating system for electric generators [1]. The Economic Dispatch is one of the most important optimization problems in electric power systems, which aims to determine the optimal allocation for all generating units located in the circuit, meet the required power demand with the lowest possible operating costs and production fuel, and eliminate all restrictions on the operation of power systems [2].

The ultimate goal of the ED problem is to minimize the cost of operations in a power generation system while supplying the power requirements [3]. Optimal load distribution can help maximize the capacity of thermal units, reduce production costs, and improve system reliability and stability [1, 4, 5].

The ED problem has become a constrained and distributed optimization problem with a nonlinear, discontinuous, non-convex, non-smooth, non-differential, and multi-modal cost function, despite the presence of valve point effects (VPE), prohibited operating zones (POZ), ramp rate limits, multiple fuel options, power balance constraint, and transmission loss [2, 6-8]. Therefore, it is challenging for classical optimization methods to obtain the global optimum for solving the ED problem [4]. These challenges include falling trapped in a local optimum, slow convergence, sensitivity, dependence on the initial starting point, and low accuracy due to linearity [2, 9-11].

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TABLE I
NOMENCLATURE

ED problem	
a_i, b_i, c_i	Fuel cost coefficients of unit *i*
e_i, f_i	Fuel cost coefficients of unit *i* considering valve-point effects
a_{ij}, b_{ij}, c_{ij}	Fuel cost coefficients for fuel type *j* of unit *i*
e_{ij}, f_{ij}	Fuel cost coefficients for fuel type *j* of unit *i* considering valve-point effects
B_{ij}, B_{0i}, B_{00}	B-matrix coefficients for transmission power loss
d	The total number of generating units
P_D	The total system load demand
P_L	The total transmission loss
P_i	The output power of unit *i*
P_i^{max}	The maximum output power of unit *i*
P_i^{min}	The minimum output power of unit *i*
$P_{i,z}^{l}$	The lower bound for prohibited zone z of unit *i*
$P_{i,z-1}^{u}$	The upper bound for prohibited zone z of unit *i*
$F_i(P_i)$	Fuel cost function of generator *i*
DR_i	The rise border values of the ramp rate limits
UR_i	The fall border values of the ramp rate limits
WMA algorithm	
P_S	Sound wave energy at the sound source
r	Euclidean distance to the sound source.
x_i^t	Current position of the *i*th woodpecker in iteration *t*
r_1, r_2, r_3, R	The random numbers
δ_i^t	The random factor for the *i*th woodpecker in iteration t
α_{gpop}	The step size of a female woodpecker toward gpop
α_{mj}	The step size of a female woodpecker toward *m*th male
x_{gpop}^t	Position of the best member of the population in iteration *t*
x_{mj}^t	The *j*th male woodpecker population in iteration *t*
t	Current iteration
t_{max}	The maximum number of iterations
$Tansig$	Tangent sigmoid function
RA	Running away function
RRA	Random Running away
GRA	Gpop Running away
$H\alpha$	The highest level α
N	Population size of woodpeckers
x_{RRA}^i	The position of a new element obtained from RRA on the *i*th woodpecker
lb	Lower bound of the variables
ub	Upper bound variables
x_{GRA}^i	The position of a new element obtained from GRA on the ith woodpecker
GRA_{bit}	Binary vector as long as the problem dimensions.
x_r	The position of the random woodpecker

Given the above-mentioned issues, metaheuristic optimization algorithms have attracted many researchers due to their high flexibility and efficiency for solving a wide range of ED problems [7, 9]. For instance, particle swarm optimization (PSO) [12, 13], grey wolf optimization (GWO) [14], modified crow search algorithm (MCSA) [15], charged system search algorithm (CSS), adaptive charged system search algorithm (ACSS) [16], improved bird swarm algorithm (IBSA) [17], dual-population adaptive differential evolution (DPADE) [18], two-stage artificial bee colony (TSABC) [19], chaotic improved harmony search algorithm (CIHSA) [20], distance-based firefly algorithm (DFA) [21], island bat algorithm (IBA) [22], chaotic bat algorithm (CBA) [23], backtracking search algorithm (BSA) [24], moth flame optimizer (MFO) [25], water cycle algorithm (WCA) [26], orthogonal learning competitive swarm optimizer (OLCSO) [27], improved fireworks algorithm with chaotic sequence operator (IFWA-CSO) [28], krill herd algorithm (KHA) and opposition-based krill herd algorithm (OKHA) [29], improved differential evolution (IDE) [30], exchange market algorithm (EMA) [11], chaotic teaching-learning-based optimization (CTLBO) [2], genetic algorithm (GA) [31], ant lion optimizer (ALO) [32], and root tree optimization algorithm (RTO) [33] have been employed to solve the ED problem.

Besides, drawing on the advantages of the evolutionary process, an artificial cooperative search algorithm (ACS) [34] has been developed to estimate the global optimum accurately for different types of complex ED problems. In [35], a novel metaheuristic algorithm named TFLWO, inspired by whirlpools created in turbulent water flows, was proposed to solve the ED problem. In [1], AGWO was proposed as the augmented version of the GWO algorithm by adding random local search mechanisms, opposite based learning (OBL), and random global exploration to solve the ED problem. In [36], the ED problem was solved by using the modified version of PSO. This algorithm includes the mutation operator, self-adaptive regulation of social parameters, and control of the inertia weight parameter (ω) by using fuzzy rules. The improved version of PSO, known as IPSO, benefits from sequences of chaos mixed with the linear reduction of parameter (ω) and the crossover operator [37]. Moreover, another method of solving the ED problem by metaheuristic algorithms is PPSO in which the PSO parameters are tuned with $phasor(\theta)$ [38]. In the recent decade, many researchers have been interested in combining metaheuristic optimization algorithms to increase efficiency and improve proposed solutions to the ED problem. For instance, the DE algorithm was combined with the quantum PSO to develop the DE-CQPSO method [39], and HPSO-MVO algorithm hybridized PSO and Multi-Verse Optimizer (MVO) [40]. The MPSO-GA algorithm combined PSO with the GA algorithm [41] and the HAAA [42], algorithm hybridized artificial algae algorithm (AAA) and simplex search method (SSM) to solve the ED problem.

This paper proposes a novel metaheuristic algorithm, named the WMA, to solve the ED problem. The WMA is inspired by the mating behavior of woodpeckers and the concept of sound intensity [43]. This algorithm has many mechanisms to effectively implement exploration and exploitation phases and strike a balance between these two phases. Since the parameters of this algorithm are regulated self-adaptively, it has the potential to solve engineering design optimization and real-world problems. The WMA is employed in this study to solve a wide range of system tests in the ED problem with a high level of nonlinearity and complexity assessment in the presence of operational constraints and limitations on generators. The results are then compared with a series of the latest and most efficient methods introduced in the research literature.

The rest of this paper consists of different sections. Section II presents the ED problem formulation. Section III introduces the WMA algorithm. In Section IV, the WMA implementation is explained to solve the ED problem. Section V reports the results of solving the evaluated test systems. Finally, conclusions are made in Section VI. In addition, Table I lists the nomenclatures of this paper.

II. ED PROBLEM MATHEMATICAL FORMULATION

A. Two types of fuel costs function for ED problem

The fuel costs of the thermal units are obtained from Eq. (1).

$$F_t = \sum_{i-1}^{d} F_i\,(P_i) = \sum_{i-1}^{d}\,(\alpha_i P_i^2 + b_i P_i + c_i) \qquad (1)$$

where P_i is the production power of the ith power generator, F_i (p) is the fuel cost of the ith power generator, and d shows the number of power plants. Moreover, the coefficients of the ith power generator units are indicated by α_i, b_i, and c_i. In ED, the production powers of the power plants are changed to minimize the cost function proposed as Eq. (1) (fuel consumption cost). Also, the cost function is not quadratic in the ED. Real generators are affected as long as steam valves are open, and the cost function is transformed into Eq. (2) by considering the valve point effect.

$$F_t = \sum_{i-1}^{d}(\alpha_i\, P_i^2 + b_i P_i + c_i + e_i * \left|sin\left(f_i * \left(P_i^{min} - P_i\right)\right)\right|) \qquad (2)$$

where e_i and f_i are the valve point loading coefficients of the ith power generator and p_i^{min} is the possible lowest production power of the ith generator.

B. Multiple fuel options

Since fuels of many thermal generators are supplied from different fuel sources such as coal, oil, and natural gas, the most profitable type of fuel should be selected within a specific area of work [6]. In this case, Eq. (1) and (2) will be transformed into Eq. (3) and (4).

$$F_i(P_i) = \begin{cases} \alpha_{i1}\,(P_i)^2 + b_{i1}(P_i) + c_{i1}\ if\ \ P_i^{min} \le P_i \le P_{i1} \\ \alpha_{i2}\,(P_i)^2 + b_{i2}(P_i) + c_{i2}\ \ \ if\ \ P_{i1} \le P_i \le P_{i2} \\ \alpha_{ik}\,(P_i)^2 + b_{ik}(P_i) + c_{ik}\ if\ P_{ik-1} \le P_i \le P_i^{max} \end{cases} \qquad (3)$$

$$F_i(P_i){:}\begin{cases} if\ \ P_i^{min} \le P_i \le P_{i1} \\ \alpha_{i1}\,(P_i)^2 + b_{i1}(P_i) + c_{i1} + \left|e_{i1} \times sin\left(f_{i1} \times \left(P_i^{min} - P_i\right)\right.\right. \\ if\ \ P_{i1} \le P_i \le P_{i2} \\ \alpha_{i2}\,(P_i)^2 + b_{i2}(P_i) + c_{i2} + \left|e_{i2} \times sin\left(f_{i2} \times (P_{i2} - P_i)\right)\right. \\ if\ \ P_{ik-1} \le P_i \le P_i^{max} \\ \alpha_{ik}\,(P_i)^2 + b_{ik}(P_i) + c_{ik} + \left|e_{ik} \times sin\left(f_{ik} \times (P_{ik} - P_i)\right)\right. \end{cases} \qquad (4)$$

where $a_{i,k}, b_{i,k}, c_{i,k}, e_{i,k}, f_{i,k}$ are the cost coefficients of the ith generator by using the kth type of fuel.

C. Transmission loss function

In an extensive interconnected network for long-distance power transmission across areas with low-load densities, the transmission loss is an essential factor affecting the optimal distribution of power. The loss is usually expressed as a quadratic function of the production power of a generator. The transmission loss is obtained by Eq. (5).

$$P_L = \sum_{i=1}^{d}\sum_{j=1}^{d}(P_i\, B_{ij} P_j) + \sum_{i=1}^{d} B_{0i}\, P_i + B_{00} \qquad (5)$$

where P_{L} is the power loss of a network and B_{0i}, B_{ij}, and B_{00} are the loss coefficients.

D. Power balance constraint

The total production power is equal to the summation of total power demanded and total transmission loss (Eq. (6)).

$$\sum_{i=1}^{d} P_i = P_D + P_L \qquad (6)$$

where $\sum_{i=1}^{d} P_i$ is the total power (T_P) generated by all of the generators, and P_{D} and P_{L} are the demanded network power and the loss network power, respectively.

E. The value of power generation constraint

The active power generation output of each thermal power unit should vary within its minimum power permitted and maximum power permitted. The value of the power generation constraint is expressed as Eq. (7).

$$P_i^{min} \le P_i \le P_i^{max} \qquad (7)$$

where p_i^{min} and p_i^{max} are the potential minimum and maximum power production of the ith generator, respectively.

F. Prohibited operating zone (POZ)

Due to work constraints in some cases, power plants are unable to generate power in all ranges between the minimum and maximum powers. These areas, in which production is impossible, are called the prohibited operating zone (POZ) and can be shown as Eq. (8).

$$P_i \in \begin{cases} P_i^{min} \le P_i \le P_{j\text{،}1}^{l} \\ P_{i\text{،}z-1}^{u} \le P_i \le P_{i\text{،}z}^{l}\ \ z = 2\text{،}3\text{،}\ \ldots\ \text{،}pz_i \\ P_{i\text{،}pz_i}^{u} \le P_i \le P_i^{max} \end{cases} \qquad (8)$$

where $P_{i\text{،}z-1}^{u}$ and $P_{i\text{،}z}^{l}$ show the upper and lower limits of the zth POZ for the ith power generation unit, respectively and pz_i is the number of POZs for the ith power generation unit.

G. Ramp rate limits

The physical limitation on and off of the generators limits the rate of change in production, as shown below. Increasing production is limited to the values obtained from Eq. (9).

$$P_i - P_i^0 \le UR_i \qquad (9)$$

Similarly, the reduction constraint is defined as Eq. (10).

$$P_i^0 - P_i \le DR_i \qquad (10)$$

where P_i^0 refers to the power in the previous stage and DR_i and UR_i shows ofare the down-ramp limit and up-ramp rate limit of the ith generating unit, respectively. Eq. (9) and (10) can be combined to express the power production range of a unit in the form of Eq. (11).

$$P_i - P_i^0 \leq UR_i \; and \; P_i^0 - P_i \leq DR_i \tag{11}$$

III. WOODPECKER MATING ALGORITHM (WMA)

Recently, the metaheuristic WMA proposed here has been inspired by the mating behavior of red-bellied woodpeckers [43, 44]. The main metaphor in the algorithm is the drumming sound of male woodpeckers made to attract female ones. The WMA has also been inspired by the notion of sound wave intensity in physics. It is a cross algorithm that includes two groups, *i.e.*, male and female woodpeckers. The female woodpeckers are the main search factors, whereas the male ones are the best positions already explored by them. In fact, the female woodpeckers are attracted by the drumming sounds made by the male ones. The level of attraction depends on the quality of the received sound in proportion to sound intensity. This quantity is expressed by Eq. (12).

$$I = \frac{P_S}{4\pi r^2} \tag{12}$$

where P_S is the sound wave energy at the sound source and r is the hearer's Euclidean distance to the sound source.

In the WMA, each female woodpecker updates its position according to Eq. (13).

$$x_i^{t+1} = x_i^t + r_1 * \frac{\delta_i^t * \left(\alpha_{gpop} * (x_{gpop}^t - x_i^t) + \alpha_{mj} * (x_{mj}^t - x_i^t)\right)}{2} \tag{13}$$

where x_i^t represents the current position of the *i*th woodpecker in iteration t, x_{gpop}^t indicates the position of the best member of the population, x_{mj}^t denotes the *j*th male woodpecker, r_1 shows a random number from a normal distribution in the range [0, 1], and δ_i^t is a random factor for the *i*th woodpecker in iteration *t*, the value of which is self-tuned during the iteration cycle using Eq. (14). The parameter α (α_{gpop}, α_{mj}) is obtained by Eq. (15). In WMA, each female woodpecker may update its position as affected by drumming from the best member of the population and the male woodpecker at the shortest distance from it. That is what x_{mj}^t refers to in this Eq.

$$\delta_i^t = r_2 * Tansig\left(1 - \frac{t}{t_{max}}\right) \tag{14}$$

where r_2 is a random number of a normal distribution in [0, 3], Tansig represents the tangent sigmoid function, t indicates the number of the current iteration, and t_{max} is the maximum number of iterations. If $\delta > 1$, the search factors diverge from the target point, which leads to exploration. If $\delta \leq 1$, the female woodpeckers converge toward the male ones, which leads to exploitation.

$$\alpha = \frac{1}{1 + SI_j^i} \tag{15}$$

where α represents the attractiveness of the *j*th male woodpecker to the *i*th female woodpecker, and SI_j^i indicates the sound intensity of the target (*j*th) woodpecker heard by the female (*i*th) one. In addition, α is the step size of a female woodpecker, specifying how close it can reach the corresponding male woodpecker

In the WMA, the RA function has been considered for stochastic moves of the factors when the drumming sounds are overloaded, the woodpecker is attacked, etc. The function includes the two operators RRA and GRA, only one of which is run for each woodpecker in each generation proportionately to the corresponding value of α, based on Eq. (16). The value of Hα is calculated using Eq. (17) in the first iteration.

$$RA = \begin{cases} RRA & if \; \alpha \geq H\alpha \\ GRA & else \end{cases} \tag{16}$$

$$H\alpha = 0.8 * \frac{\sum_1^{n-1} \alpha_{gpop}^i}{N-1} \tag{17}$$

where N is the population size of woodpeckers and $H\alpha$ is the highest level α.

RRA is a totally stochastic move across the search space that is focused directly on exploration. It is implemented using Eq. (18).

$$x_{RRA}^i = lb - (lb - ub) * r_3 \tag{18}$$

where x_{RRA}^i is the position of a new element obtained from RRA on the *i*th woodpecker, lb represents the lower bound of the variables, ub indicates their upper bound, and r_3 is a random number from a normal distribution in the range [0, 1].

The GRA operator causes stochastic changes in some of the variables concerning the female woodpeckers based on the best male one and the position of another random woodpecker. The operator is applied based on Eq. (19).

$$x_{GRA}^i = x_i^t + GRA_{bit} * \left\{\left(x_{gpop}^t - x_r\right) * R\right\} \tag{19}$$

where x_{GRA}^i is the position of a new element obtained from GRA on the *i*th woodpecker, R is random numbers from a random distribution in the range [-1, 1], x_r is the position of the random woodpecker, x_i^t is that of the *i*th female woodpecker, and x_{gpop}^t is the position of the best woodpecker throughout the population. Also, $\mathrm{GRA_{bit}}$ is a binary vector as long as the problem dimensions.

IV. WMA ALGORITHM APPLIED TO ED

In this section, the steps of the proposed model for solving the ED problem are provided. In other words, we would explain how to adapt WMA for ED problems. Also, Fig. 1 shows the flowchart of the proposed model.

Step 1: The population of woodpeckers is initialized randomly based on the lower and upper bounds of the production power of each active generator. In fact, each woodpecker is a potential solution in the form of a vector and each item of this algorithm is considered the proposed production power for a corresponding active generator. The magnitude of this vector is equal to the number of active generators in the studied power system. In this step, if a woodpecker does not comply with the terms of the operational and production restrictions of the ED problem and the proposed answer has a violation, it will be reinitialized. With this strategy, the initial population of woodpeckers will be inside a favorable area.

Step 2: The fitness (the generation fuel cost) is calculated for each candidate solution in the population of woodpeckers using Eq. (3) and (4). The fitness value reflects the distance of each female woodpecker to the male woodpecker.

Step 3: The population of woodpeckers is sorted based on the generation fuel cost and divided into two categories of male and female woodpeckers. In each generation, the fittest search agents are chosen to be marked as male woodpeckers.

Step 4: In the population of woodpeckers, each member updates its position based on Eq. (13) and/or RA function. In fact, the position of the search agents is a potential power generation plan for the generators.

Step 5: In this step, the feasibility of the candidate solutions regarding the equality and inequality constraints of POZ, ramp rate limits, minimum and maximum generation limit, and the load balance equality constraint (Eq. (6)) are investigated. In cases of upper and lower limits of power generation, as well as ramp rate limits, if the recommended power is less than the acceptable power generation range, the value is shifted to the minimum acceptable value. Conversely, if the power generation of an agent is more than the acceptable range, this value is shifted to the maximum acceptable value.

In this paper, the penalty function is used to handle the equality constraint of the load balance (Eq. (20)). In fact, adding the penalty term to the cost function turns the constraint into an inequality constraint, which can then be handled. In this case, if a solution does not satisfy the equality constraint, the cost would be non-zero and the added penalty term would increase the cost function, which woul lead to its elimination. Conversely, in cases where the equality constraint is satisfied, violation (V) would be zero. Therefore, the optimal generation cost stays the same.

$$F_i(P_i)_{penalty} = F_i(P_i) \times (1 + \varphi \times V) \tag{20}$$

where $F_i(P_i)_{penalty}$ is the fuel cost defined based on the penalty function and $F_i(P_i)$ is the fuel cost. φ, the penalty coefficient, is a relatively large positive real number that is defined as the penalty of an infeasible solution. Its value depends on the complexity of the search space and the optimization problem and is determined via trial and error. V indicates the degree to which a solution violates the constraints of the problem, which is a number in the range [0,1]. The larger the error is, the greater the penalty of the infeasible solution would be. The value V is determined using Eq. (21).

$$V = max\left(\left\{1 - \frac{T_P - P_L}{P_D}\right\}, 0\right) \tag{21}$$

where max is the maximum operator, and T_P, P_L, and P_D are the total generated power, transmission loss, and the load demand of the network, respectively.

Steps 3 and 5 will be repeated until the termination conditions are met for the WMA. Finally, the best solution with the least fuel cost would be chosen as the most optimal power generation plan for the generators and the output of the algorithm.

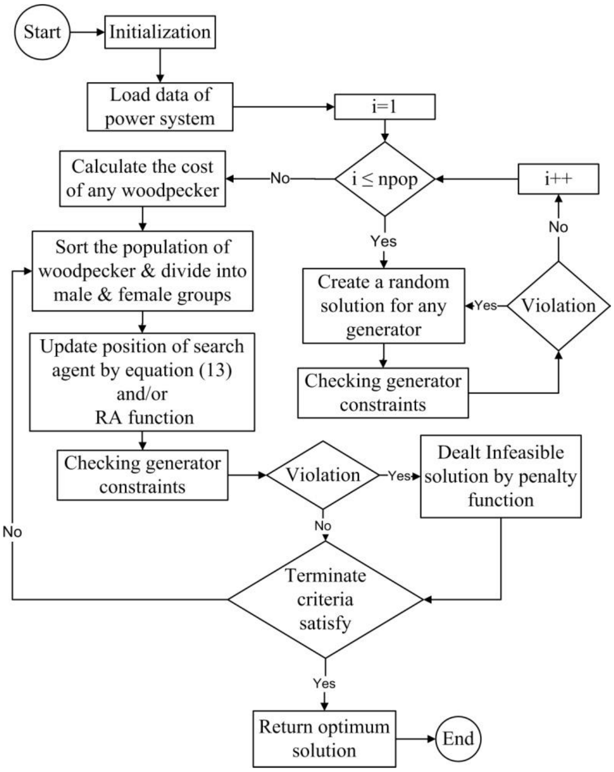

Fig. 1. The flowchart of the proposed model.

V. CASE STUDIES AND EXPERIMENTAL RESULTS

In this section, the WMA is implemented and evaluated on six different real-world test systems for electrical power engineering design. In all the tests, there were 50 woodpeckers with 200 possible iterations. The WMA was executed 50 times separately on each test system to report the average (avg), best (B), and worst (W) solutions. All tests were performed on a system with a processor Intel Core™ i7–7500U 2.7 GHz and an 8GB RAM DDR4. All tests were run in MATLAB 2017a. The characteristics of the power test systems are summarized in Table II and the details of the generator unit data are given in the appendix.

TABLE II
CHARACTERISTICS OF SIX DIFFERENT TEST SYSTEMS

Characteristics	Case 1	Case 2	Case 3	Case4	Case 5	Case 6
VPE					❖	❖
Transmission lost	❖	❖	❖			
POZ	❖	❖			❖	
Ramp rate limits	❖	❖			❖	
multiple fuel options					❖	❖
Unit number	6	15	20	38	140	10
P_D	1263	2630	2500	6000	49342	2700

A. *Test System 1*

This test was conducted to analyze a real system including six thermal generators by considering POZ and ramp rate limits, as well as the transmission loss and a quadratic cost function. The total load demand is considered P_D = 1263 MW. The operational characteristics of this test system including fuel cost coefficients and generator capacities are listed in [45]. Table III compares the statistical results of WMA with a series of methods introduced in the literature. Accordingly, the WMA algorithm produced the lowest production fuel cost of all of the evaluated methods by outperforming other compared algorithms. The optimum and feasible dispatch of generators and transmission loss obtained by the WMA in this power system are tabulated in Table IV.

TABLE III
COMPARISON OF STATISTICAL RESULTS OF THE OPTIMIZATION METHODS FOR THE TEST SYSTEM 1

Methods	B ($/h)	Ave ($/h)	W ($/h)	Time
WMA	15443.0796	15443.0796	15443.0799	0.103
PSO [36]	15450.0000	15454.0000	15450.0000	NA
MCSA [15]	15449.1672	15449.2358	15449.3854	NA
NAPSO[36]	15443.7657	15443.7657	15443.7657	NA
FAPSO[36]	15445.2440	15448.0520	15451.6300	NA
CSS [16]	15448.3972	15557.8899	16616.3788	1.04
ACSS [16]	15443.5562	15458.2023	15490.6899	1.08
HBB [46]	15444.2600	15446.4600	15448.8900	5.6554
IDPSO[12]	15449.8900	15450.7000	NA	0.727

* Time is the average time (s) of simulation and NA is not available.

B. *Test System 2*

This section evaluates a system composed of 15 generators. This test system includes POZ, ramp rate limits, and transmission loss. The physical properties of these generators are presented in [6]. This power system had a quadratic cost function with total load demand P_D = 2630 MW. Table V presents the statistical results of testing Test System 2 through the WMA. Moreover, Table 5 draws a comparison between the WMA results and those of other methods proposed to solve the ED problem. Accordingly, the WMA algorithm yielded much more optimal and better results at lower fuel costs. These results prove the ability of the WMA to solve complex ED problems. The optimum and feasible dispatch of the generators and transmission loss obtained by the WMA in Test System 2 are tabulated in Table VI.

TABLE IV
OPTIMAL DISPATCH RESULTS OF THE WMA ALGORITHM FOR TEST SYSTEM 1

Generators						
P1-P6	447.34	173.28	263.38	138.90	165.42	87.12
T_P (MW)	1275.45	P_L (MW)	12.45	Violation: 0.0		

C. *Test System 3*

Test System 3 includes 20 thermal generators with quadratic cost functions and total load demand P_D = 2500 MW. This test system considers the transmission loss. the operational properties of thermal generators and the information on the transfer network loss are mentioned in [6]. Table VII shows the statistical results of Test System 3 with the WMA algorithm and draws a comparison between the WMA results and those of ADE-MMS [6], FMLP [7], HOSMEPO [47], IEAM-R[48], IA_EDP [49], and CBA [23]. Accordingly, the WMA yielded a lower fuel cost than other methods. As a result, the WMA outperformed all of the other compared algorithms. The optimum dispatch of the generators and transmission loss obtained by the WMA in this power system are presented in Table VIII.

TABLE V
COMPARISON OF STATISTICAL RESULTS OF THE OPTIMIZATION METHODS FOR TEST SYSTEM 2

Methods	B ($/h)	Ave ($/h)	W ($/h)	Time
WMA	32679.0	32679.1	32679.3	0.127
CS-CLM [50]	32704.5	32704.5	32704.5	0.225
C-MIMO-CSO [51]	32701.2	32701.2	32701.2	2. 72
IODPSO-G [52]	32692.4	32692.4	32692.4	NA
IODPSO-I [52]	32692.4	32692.4	32692.4	NA
WCA [26]	32704.4	32704.5	32704.5	NA
OLCSO [27]	32692.4	32692.4	32692.4	3.5
CSS [16]	32693.3	32798.4	32971.1	2.5
IBSA [17]	32703.7	32703.8	32704.1	NA
ICA [53]	32715.4	NA	NA	NA

TABLE VI
OPTIMAL DISPATCH RESULTS OF THE WMA ALGORITHM FOR TEST SYSTEM 2

Generators					
P1-P5	455	455	130	130	240.107
P6-P10	460	465	60	25	25.0036
P11-P15	77.2848	79.9977	25	15	15
T_P (MW): 2657.3931		P_L (MW): 27.3931		Violation: 0.0	

TABLE VII
COMPARISON OF STATISTICAL RESULTS OF THE OPTIMIZATION METHODS FOR THE TEST SYSTEM 3

Methods	B($/h)	Ave($/h)	W ($/h)	Time
WMA	62448.141	62448.748	62450.731	0.453
ADE-MMS	62456.507	62456.638	62457.061	NA
FMLP	62456.633	NA	NA	3.154
HOSMEPO	62453.490	NA	NA	NA
IEAM-R	62452.861	NA	NA	NA
IA_EDP	62466.804	62487.511	62528.987	1.928
CBA	62456.6328	62456.6348	62501.6714	1.16

TABLE VIII
OPTIMAL DISPATCH RESULTS OF THE WMA ALGORITHM FOR TEST SYSTEM 3

Generators					
P1-P5	512.005	170.009	126.325	102.596	113.783
P6-P10	74.5664	115.068	116.257	99.5265	105.952
P11-P15	150.473	292.617	120.657	31.0146	115.195
P16-P20	36.2376	66.7766	88.7096	99.0573	54.7075
T_P (MW): 2591.5331		P_L: 91.5331		Violation: 0.0	

D. *Test System 4*

This section evaluates a power system with 38 thermal generators and a quadratic cost function. The total load demand of this test system is P_D = 6000 MW, and the transfer line loss was disregarded. The operational properties of this test system are mentioned in [1]. Table IX presents the statistical results of the WMA on Test System 4 and compares the performance of the WMA with that of the ADE-MMS [6], AGWO [1], GWO [3], MHS [54], and IDE [30]. Accordingly, the WMA managed to have a lower fuel cost than other methods by outperforming them significantly. As a result, the WMA can solve complex ED problems. The optimum dispatch of the generators obtained by the WMA in this power system is tabulated in Table X.

TABLE IX
COMPARISON OF STATISTICAL RESULTS OF THE OPTIMIZATION METHODS FOR TEST SYSTEM 4

Methods	B($/h)	Ave($/h)	W($/h)	Time
WMA	9025100.059	9025103.675	9025110.682	1.178
ADE-MMS	9417235.787	9417235.789	9417235.793	NA
AGWO	9417226.000	9417229.000	9417231.000	NA
GWO	9419270.188	9419978.978	9421100.000	9.457
EP-EPSO	9387925.497	NA	NA	NA
IDE	9417235.786	9417235.786	9417235.786	9.149

TABLE X
OPTIMAL DISPATCH RESULTS OF THE WMA ALGORITHM FOR TEST SYSTEM 4

Generators					
P1-P5	435.451	418.073	388.040	499.999	423.757
P6-P10	439.917	400.778	414.469	114.051	114.115
P11-P15	144.912	119.063	110	90.1284	82
P16-P20	120.008	159.679	65.690	65.030	271.986
P21-P25	271.991	259.382	125.012	10.5565	108.278
P26-P30	84.109	39.487	26.5991	20.0002	20
P31-P35	20.6661	20.115	25.499	18	8
P36-P38	25.149	20	20.006		
T_P (MW): 6000				Violation: 0.0	

E. *Test System 5*

The most extensive and complicated test system, evaluated in this paper, is a large-scale power system including 140 power generators named the Korean system. This system includes VPE, POZ, ramp rate limits, and multiple fuel options with total load demand P_D =49342 MW. The transfer network loss is disregarded in this test system. It is a fossil fuel-based power system, comprising 40 thermal generating units, 51 gas units, 20 nuclear units, and 29 oil units. Out of the 140 units, 6 thermal units, 4 gas units, and 2 oil units have non-convex fuel cost function addressing valve loading effects, and some units having prohibited operating zones. The operational properties of this test system are mentioned in [6]. Table XI shows the statistical results of the WMA in solving Test System 5 and draws a comparison between the best results of the WMA and the other methods proposed in the research literature. Accordingly, the WMA managed to obtain the lowest fuel cost. The more optimal solution provided by the WMA algorithm proves its superiority and efficiency in comparison with all of the other evaluated algorithms. The optimum dispatch of the generators obtained by the WMA in this power system is tabulated in Table XII.

TABLE XI
COMPARISON OF STATISTICAL RESULTS OF THE OPTIMIZATION METHODS FOR TEST SYSTEM 5

Methods	B($/h)	Ave($/h)	W ($/h)	Time
WMA	1559682.1	1559684.0	1559688.1	2.44
AGWO [1]	1559708.0	1559708.0	1559709.0	NA
CS-CLM [50]	1559848.4	1559908.5	1559993.2	11.9
CL_CLM [50]	1559708.4	1559708.4	1559708.4	9 .25
AAA [42]	1559909.0	1560060.8	1560303.0	166
HAAA [42]	1559710.0	1559712.9	1559731.0	112
C- CSO [51]	1559712.0	1559715.7	1559734.0	32.3
OGWO [14]	1559709.9	1559713.2	1559743.5	41.8
GWO[14]	1559953.2	1560132.9	1560228.4	45.5
KHA [29]	1560173.9	1560176.7	1560177.9	30.5
OKHA [29]	1560146.9	1560148.9	1560149.9	25.7

TABLE XII
OPTIMAL DISPATCH RESULTS OF THE WMA ALGORITHM FOR TEST SYSTEM 5

Generators					
P1-5	115	188.99	190	190	168.55
P6- 10	190	490	490	496	496
P11- 15	496	496	506	509	506
P16- 20	505	506	506	505	505
P21- 25	505	505	505	505	536.9
P26- 30	536.9	549	549	501	501
P31-35	506	505.9	505.98	505.98	500
P36-40	499.97	241	241	774	768.98
P41-45	3	3	250	245.9	250
P46-50	250	240.95	249.98	249.98	250
P51-55	165	165	165	165	180
P56-60	180	103	198	311.98	281.17
P61-65	163	95	160	160	490
P66-70	197	490	489.99	130	234.80
P71-75	137	325.44	195	175	175.00
P76-80	175	175	330	530.96	530.99
P81-85	397	56	115.01	115.03	115
P86-90	207	207.00	175	175.00	175.00
P91-95	175	579.24	647	984	977.99
P96-100	681.89	720	717.58	719.9	964
P101-105	957.86	1006.79	1005.5	1013	1019.99
P106-110	954	951.99	1006	1012.99	1020.97
P111-115	1014	95	95	94	244
P116-120	244.00	244	95.00	95.00	116
P121-125	175	2	4	15	9
P126-130	12	10	112	4	5
P131-135	5	50.00	5	42	42
P136-140	41	17	7	7	26
T_P: 49342		Violation: 0.0			

F. *Test System 5*

This power system includes 10 generators with the effects of valve point effect, multiple fuel options, and disregarding the transfer line loss. The load demand of this test system $P_D =$ 2700 MW. The physical properties of the generators and multiple fuel options information of the thermal units are mentioned in [31]. The optimum dispatch of the generators, fuel type, and fuel cost obtained by the WMA in this power system are tabulated in Table XIII. Table XIV shows the statistical results of executing Test System 6 through the WMA and compares the results of the WMA algorithm with the other methods proposed to solve the ED problem. Accordingly, the WMA yielded much more optimal and better results at the lowest fuel cost. These results prove that the

WMA can solve complex ED problems.

TABLE XIII
OPTIMAL DISPATCH RESULTS OF THE WMA ALGORITHM FOR TEST SYSTEM 6

Generators					
P1-P5	215.52	214.25	281.45	242.39	276.9
Fuel type	2	1	1	3	1
P6-P10	237.25	292.94	239.3	424.68	275.3
Fuel type	3	1	3	3	1
T_P (MW): 2700			Violation : 0.0		

TABLE XIV
COMPARISON OF STATISTICAL RESULTS OF THE OPTIMIZATION METHODS FOR TEST SYSTEM 6

Methods	B($/h)	Ave($/h)	W ($/h)	Time
WMA	623.544	623.56	623.58	0.868
PPSO [9]	623.83	623.84	623.85	NA
M2 [55]	623.81	623.81	NA	0.59
TFWO [35]	623.83	623.84	623.85	NA
CTPSO [37]	623.83	623.88	623.83	3.2
NAPSO [36]	623.62	623.63	623.68	2.8
FAPSO [36]	624.22	624.28	624.30	5.9
DPADE [18]	623.82	623.82	623.82	10.34
C-CSO [51]	623.83	623.83	623.83	9.261
MCSA [15]	623.83	623.83	623.85	NA
SDP [56]	623.81	NA	NA	NA
IPSO-G [52]	623.83	623.84	623.83	NA
IPSO-l [52]	623.83	623.83	623.83	NA
TSABC [19]	623.83	623.85	623.87	2.32

Fig. 2 in the Appendix shows the convergence diagram of the WMA algorithm of all evaluated systems. As can be seen, in all evaluated systems, the WMA showed a fast, smooth, and steady convergence.

VI. CONCLUSION

The ED problem is one of the most fundamental optimization problems in power engineering. Optimizing this problem can reduce the production cost and increase the reliability of power generators. In this paper, the WMA algorithm is employed to solve the ED problem by considering the operational conditions and production constraints of different generators such as valve point effect, multiple fuel options, ramp rate limits, prohibited operating zone, and power balance constraint, as well as the loss over the power transmission line. The WMA algorithm is inspired by the mating behavior of woodpeckers and the physics law of sound intensity. The WMA is evaluated on six real-world test systems and then compared with a series of novel and efficient methods proposed in the research literature. The WMA managed to yield promising results at the lowest fuel cost among all other methods. The simulation results prove the ability and efficiency of the WMA in solving the complex ED problem. This algorithm can solve other real-world optimization and power engineering design problems as well.

Appendix

TABLE XV
DATA FOR TEST SYSTEM 1

$Unit_i$	P_i^{min}	P_i^{max}	a_i	b_i	c_i	UR_i	DR_i	P_i^0	POZ
1	100	500	240	7	0.0070	80	120	440	[210,240] [350,380]
2	50	200	200	10	0.0095	50	90	170	[90,110][140,160]
3	80	300	220	8.5	0.0090	65	100	200	[150,170][210,240]
4	50	150	200	11	0.0090	50	90	150	[80,90][110,120]
5	50	200	220	10.5	0.0080	50	90	190	[90,110][140,150]
6	50	120	190	12	0.0075	50	90	110	[75,85][100,105]

TABLE XVI
DATA FOR TEST SYSTEM 2

$Unit_i$	P_i^{min}	P_i^{max}	a_i	b_i	c_i	UR_i	DR_i	P_i^0	POZ
1	150	455	671	10.1	0.000299	80	120	400	
2	150	455	574	10.2	0.000183	80	120	300	[185,225][305,335][420,450]
3	20	130	374	8.80	0.001126	130	130	105	
4	20	130	374	8.80	0.001126	130	130	100	
5	150	470	461	10.40	0.000205	80	120	90	[180,200][305,335][390,420]
6	135	460	630	10.10	0.000301	80	120	400	[230,255][365,395][430,455]
8	60	300	227	11.2	0.000338	65	100	95	
9	25	162	173	11.2	0.000807	60	100	105	
10	25	160	175	10.7	0.001203	60	100	110	
11	20	80	186	10.2	0.003586	80	80	60	
12	20	80	230	9.90	0.005513	80	80	40	[30,40][55,65]
13	25	85	225	13.1	0.000371	80	80	30	
14	15	55	309	12.1	0.001929	55	55	20	
15	15	55	323	12.4	0.004447	55	55	20	

TABLE XVII

DATA FOR TEST SYSTEM 3

$Unit_i$	P_i^{min}	P_i^{max}	a_i	b_i	c_i	$Unit_i$	P_i^{min}	P_i^{max}	a_i	b_i	c_i
1	150	600	0.00068	18.2	1000	11	100	300	0.005	16.69	800
2	50	200	0.00071	19.3	970	12	150	500	0.003	16.76	970
3	50	200	0.0065	19.8	600	13	40	160	0.009	17.36	900
4	50	200	0.005	19.1	700	14	20	130	0.005	18.7	700
5	50	160	0.00738	18.1	420	15	25	185	0.004	18.7	450
6	20	100	0.00612	19.3	360	16	20	80	0.071	14.26	370
7	25	125	0.0079	17.1	490	17	30	85	0.009	19.14	480
8	50	150	0.00813	18.9	660	18	30	120	0.007	18.92	680
9	50	200	0.00522	18.3	765	19	40	120	0.006	18.47	700
10	30	150	0.00573	18.9	770	20	30	100	0.008	19.79	850

TABLE XVIII

DATA FOR TEST SYSTEM 4

$Unit_i$	P_i^{min}	P_i^{max}	a_i	b_i	c_i	$Unit_i$	P_i^{min}	P_i^{max}	a_i	b_i	c_i
1	220	550	0.3133	797	64782	20	120	272	0.492	696.1	39197
2	220	550	0.3133	797	64782	21	120	272	0.573	660.2	45576
3	200	500	0.3127	796	64670	22	110	260	0.357	803.2	28770
4	200	500	0.3127	796	64670	23	80	190	0.942	818.2	36902
5	200	500	0.3127	796	64670	24	10	150	52.12	33.5	105510
6	200	500	0.3127	796	64670	25	60	125	1.142	805.4	22233
7	200	500	0.3127	796	64670	26	55	110	2.028	707.1	30953
8	200	500	0.3127	796	64670	27	35	75	3.074	833.6	17044
9	114	500	0.7075	916	172832	28	20	70	16.77	2188.7	81079
10	114	500	0.7075	916	172832	29	20	70	26.36	1024.4	124767
11	114	500	0.7515	884	176003	30	20	70	30.58	837.1	121915
12	114	500	0.7083	884	173028	31	20	70	25.1	1305.2	120780
13	110	500	0.4211	1250	91340	32	20	60	33.72	716.6	104441
14	90	365	0.5145	1299	63440	33	25	60	23.92	1633.9	83224
15	82	365	0.5691	1299	65468	34	18	60	32.56	969.6	111281
16	120	325	0.5691	1291	77282	35	8	60	18.36	2625.8	64142
17	65	315	2.5881	238	190928	36	25	60	23.92	1633.9	103519
18	65	315	3.8734	1150	285372	37	20	38	8.482	694.7	13547
19	65	315	3.6842	1269	271676	38	20	38	9.693	655.9	13518

TABLE XIX

DATA FOR TEST SYSTEM 5 (C: COAL, O: OIL, N: NUCLEAR, L: LNG)

$Unit_i$	a_i	b_i,	c_i	P_i^{min}	P_i^{max}	UR_i	DR_i	P_i^0	$Unit_i$	a_i	b_i,	c_i	P_i^{min}	P_i^{max}	UR_i	DR_i	P_i^0
C01	0.032888	61.242	1220.645	71	119	30	120	98.4	L44	0.014382	93.966	3174.939	207	307	120	180	252.0
C02	0.008280	41.095	1315.118	120	189	30	120	134.	L45	0.013161	94.723	3218.359	207	307	120	180	221.
C03	0.003849	46.310	874.288	125	190	60	60	141.5	L46	0.016033	66.919	3723.822	175	345	318	318	245.9
C04	0.003849	46.310	874.288	125	190	60	60	183.3	L47	0.013653	68.185	3551.405	175	345	318	318	247.9
C05	0.042468	54.242	1976.469	90	190	150	150	125.0	L48	0.028148	60.821	4322.615	175	345	318	318	183.6
C06	0.014992	61.215	1338.087	90	190	150	150	91.3	L49	0.013470	68.551	3493.739	175	345	318	318	288.0
C07	0.007039	11.791	1818.299	280	490	180	300	401.1	C01	0.000064	2.842	226.799	360	580	18	18	557.4
C08	0.003079	15.055	1133.978	280	490	180	300	329.5	N02	0.000252	2.946	382.932	415	645	18	18	529.5
C09	0.005063	13.226	1320.636	260	496	300	510	386.1	N03	0.000022	3.096	156.987	795	984	36	36	800.8
C10	0.005063	13.226	1320.636	260	496	300	510	427.3	N04	0.000022	3.040	154.484	795	978	36	36	801.5
C11	0.005063	13.226	1320.636	260	496	300	510	412.2	N05	0.000203	1.709	332.834	578	682	138	204	582.7
C12	0.003552	14.498	1106.539	260	496	300	510	370.1	N06	0.000198	1.668	326.599	615	720	144	216	680.7
C13	0.003901	14.651	1176.504	260	506	600	600	301.8	N07	0.000215	1.789	345.306	612	718	144	216	670.7
C14	0.003901	14.651	1176.504	260	509	600	600	368.0	N08	0.000218	1.815	350.372	612	720	144	216	651.7
C15	0.003901	14.651	1176.504	260	506	600	600	301.9	N09	0.000193	2.726	370.377	758	964	48	48	921.0
C16	0.003901	14.651	1176.504	260	505	600	600	476.4	N10	0.000197	2.732	367.067	755	958	48	48	916.8
C17	0.002393	15.669	1017.406	260	506	600	600	283.1	N11	0.000324	2.651	124.875	750	1007	36	54	911.9
C18	0.002393	15.669	1017.406	260	506	600	600	414.1	O05	0.030266	64.125	4965.124	244	379	480	480	318.4
C19	0.003684	14.656	1229.131	260	505	600	600	328.0	O06	0.030266	64.125	4965.124	244	379	480	480	335.8
C20	0.003684	14.656	1229.131	260	505	600	600	389.4	O07	0.024027	76.129	2243.185	95	190	240	240	151.0
C21	0.003684	14.656	1229.131	260	505	600	600	354.7	O08	0.001580	81.805	2290.381	95	189	240	240	129.5
C22	0.003684	14.656	1229.131	260	505	600	600	262.0	O09	0.022095	81.140	1681.533	116	194	120	120	130.0
C23	0.004004	14.378	1267.894	260	505	600	600	461.5	O10	0.076810	46.665	6743.302	175	321	180	180	218.9
C24	0.003684	14.656	1229.131	260	505	600	600	371.6	O11	0.953443	78.412	394.398	2	19	90	90	5.4
C25	0.001619	16.261	975.926	280	537	300	300	462.6	O12	0.000044	112.09	1243.165	4	59	90	90	45.0
C26	0.005093	13.362	1532.093	280	537	300	300	379.2	O13	0.072468	90.871	1454.740	15	83	300	300	20.0
C27	0.000993	17.203	641.989	280	549	360	360	530.8	O14	0.000448	97.116	1011.051	9	53	162	162	16.3
C28	0.000993	17.203	641.989	280	549	360	360	391.9	O15	0.599112	83.244	909.269	12	37	114	114	20.0
C29	0.002473	15.274	911.533	260	501	180	180	480.1	O16	0.244706	95.665	689.378	10	34	120	120	22.1
C30	0.002547	15.212	910.533	260	501	180	180	319.0	O17	0.000042	91.202	1443.792	112	373	**1080**	**1080**	125.0
C31	0.003542	15.033	1074.810	260	506	600	600	329.5	O18	0.085145	104.50	535.553	4	20	60	60	10.0
C32	0.003542	15.033	1074.810	260	506	600	600	333.8	O19	0.524718	83.015	617.734	5	38	66	66	13.0
C33	0.003542	15.033	1074.810	260	506	600	600	390.0	O20	0.176515	127.79	90.966	5	19	12	6	7.5
C34	0.003542	15.033	1074.810	260	506	600	600	432.0	O21	0.063414	77.929	974.447	50	98	300	300	53.2
C35	0.003132	13.992	1278.460	260	500	660	660	402.0	O22	2.740485	92.779	263.810	5	10	6	6	6.4
C36	0.001323	15.679	861.742	260	500	900	900	428.0	O23	0.112438	80.950	1335.594	42	74	60	60	69.1

Table XIX (CONTINUED)

Unit_i	a_i	b_i,	c_i	P_i^{min}	P_i^{max}	UR_i	DR_i	P_i^0	Unit_i	a_i	b_i,	c_i	P_i^{min}	P_i^{max}	UR_i	DR_i	P_i^0
C37	0.002950	16.542	408.834	120	241	180	180	178.4	O24	0.041529	89.073	1033.871	42	74	60	60	49.9
C38	0.002950	16.542	408.834	120	241	180	180	194.1	O25	0.000911	161.29	1391.325	41	105	528	528	91.0
C39	0.000991	16.518	1288.815	423	774	600	600	474.0	O26	0.005245	161.83	4477.110	17	51	300	300	41.0
C40	0.001581	15.815	1436.251	423	769	600	600	609.8	O27	0.234787	84.972	57.794	7	19	18	30	13.7
L01	0.902360	75.464	669.988	3	19	210	210	17.8	O28	0.234787	84.972	57.794	7	19	18	30	7.4
L02	0.110295	129.544	134.544	3	28	366	366	6.9	O29	1.111878	16.087	1258.437	26	40	72	120	28.
L01	0.024493	56.613	3427.912	160	250	702	702	224.3	L44	0.014382	93.966	3174.939	207	307	120	180	252.0
L02	0.029156	54.451	3751.772	160	250	702	702	210.0	L45	0.013161	94.723	3218.359	207	307	120	180	221.0
L03	0.024667	54.736	3918.780	160	250	702	702	212.0	L46	0.016033	66.919	3723.822	175	345	318	318	245.9
L04	0.016517	58.034	3379.580	160	250	702	702	200.8	L47	0.013653	68.185	3551.405	175	345	318	318	247.9
L05	0.026584	55.981	3345.296	160	250	702	702	220.0	L48	0.028148	60.821	4322.615	175	345	318	318	183.6
L06	0.007540	61.520	3138.754	160	250	702	702	232.9	L49	0.013470	68.551	3493.739	175	345	318	318	288.0
L07	0.016430	58.635	3453.050	160	250	702	702	168.0	C01	0.000064	2.842	226.799	360	580	18	18	557.4
L08	0.045934	44.647	5119.300	160	250	702	702	208.4	N02	0.000252	2.946	382.932	415	645	18	18	529.5
L09	0.000044	71.584	1898.415	165	504	1350	1350	443.9	N03	0.000022	3.096	156.987	795	984	36	36	800.8
L10	0.000044	71.584	1898.415	165	504	1350	1350	426.0	N04	0.000022	3.040	154.484	795	978	36	36	801.5
L11	0.000044	71.584	1898.415	165	504	1350	1350	434.1	N05	0.000203	1.709	332.834	578	682	138	204	582.7
L12	0.000044	71.584	1898.415	165	504	1350	1350	402.5	N06	0.000198	1.668	326.599	615	720	144	216	680.7
L13	0.002528	85.120	2473.390	180	471	1350	1350	357.4	N07	0.000215	1.789	345.306	612	718	144	216	670.7
L14	0.000131	87.682	2781.705	180	561	720	720	423.0	N08	0.000218	1.815	350.372	612	720	144	216	651.7
L15	0.010372	69.532	5515.508	103	341	720	720	220.0	N09	0.000193	2.726	370.377	758	964	48	48	921.0
L16	0.007627	78.339	3478.300	198	617	2700	2700	369.4	N10	0.000197	2.732	367.067	755	958	48	48	916.8
L17	0.012464	58.172	6240.909	100	312	1500	1500	273.5	N11	0.000324	2.651	124.875	750	1007	36	54	911.9
L18	0.039441	46.636	9960.110	153	471	1656	1656	336.0	N12	0.000344	2.798	130.785	750	1006	36	54	898.0
L19	0.007278	76.947	3671.997	163	500	2160	2160	432.0	N13	0.000690	1.595	878.746	713	1013	30	30	905.0
L20	0.000044	80.761	1837.383	95	302	900	900	220.0	N14	0.000650	1.503	827.959	718	1020	30	30	846.5
L21	0.000044	70.136	3108.395	160	511	1200	1200	410.6	N15	0.000233	2.425	432.007	791	954	30	30	850.9
L22	0.000044	70.136	3108.395	160	511	1200	1200	422.7	N16	0.000239	2.499	445.606	786	952	30	30	843.7
L23	0.018827	49.840	7095.484	196	490	1014	1014	351.0	N17	0.000261	2.674	467.223	795	1006	36	36	841.4
L24	0.010852	65.404	3392.732	196	490	1014	1014	296.0	N18	0.000259	2.692	475.940	795	1013	36	36	835.7
L25	0.018827	49.840	7095.484	196	490	1014	1014	411.1	N19	0.000707	1.633	899.462	795	1021	36	36	828.8
L26	0.018827	49.840	7095.484	196	490	1014	1014	263.2	N20	0.000786	1.816	1000.367	795	1015	36	36	846.0
L27	0.034560	66.465	4288.320	130	432	1350	1350	370.3	O01	0.014355	89.830	1269.132	94	203	120	120	179.0
L28	0.081540	22.941	13813.001	130	432	1350	1350	418.7	O02	0.014355	89.830	1269.132	94	203	120	120	120.8
L29	0.023534	64.314	4435.493	137	455	1350	1350	409.6	O03	0.014355	89.830	1269.132	94	203	120	120	121.0
L30	0.035475	45.017	9750.750	137	455	1350	1350	412.0	O04	0.030266	64.125	4965.124	244	379	480	480	317.4
L31	0.000915	70.644	1042.366	195	541	780	780	423.2	O05	0.030266	64.125	4965.124	244	379	480	480	318.4
L32	0.000044	70.959	1159.895	175	536	1650	1650	428.0	O06	0.030266	64.125	4965.124	244	379	480	480	335.8
L33	0.000044	70.959	1159.895	175	540	1650	1650	436.0	O07	0.024027	76.129	2243.185	95	190	240	240	151.0
L34	0.001307	70.302	1303.990	175	538	1650	1650	428.0	O08	0.001580	81.805	2290.381	95	189	240	240	129.5
L35	0.000392	70.662	1156.193	175	540	1650	1650	425.0	O09	0.022095	81.140	1681.533	116	194	120	120	130.0
L36	0.000087	71.101	2118.968	330	574	1620	1620	497.2	O10	0.076810	46.665	6743.302	175	321	180	180	218.9
L37	0.000521	37.854	779.519	160	531	1482	1482	510.0	O11	0.953443	78.412	394.398	2	19	90	90	5.4
L38	0.000498	37.768	829.888	160	531	1482	1482	470.0	O12	0.000044	112.09	1243.165	4	59	90	90	45.0
L39	0.001046	67.983	2333.690	200	542	1668	1668	464.1	O13	0.072468	90.871	1454.740	15	83	300	300	20.0
L40	0.132050	77.838	2028.945	56	132	120	120	118.1	O14	0.000448	97.116	1011.051	9	53	162	162	16.3
L41	0.096968	63.671	4412.017	115	245	180	180	141.3	O15	0.599112	83.244	909.269	12	37	114	114	20.0
L42	0.054868	79.458	2982.219	115	245	120	180	132.0	O16	0.244706	95.665	689.378	10	34	120	120	22.1
L43	0.054868	79.458	2982.219	115	245	120	180	135.0	O17	0.000042	91.202	1443.792	112	373	**1080**	**1080**	125.0
N12	0.000344	2.798	130.785	750	1006	36	54	898.0	O18	0.085145	104.50	535.553	4	20	60	60	10.0
N13	0.000690	1.595	878.746	713	1013	30	30	905.0	O19	0.524718	83.015	617.734	5	38	66	66	13.0
N14	0.000650	1.503	827.959	718	1020	30	30	846.5	O20	0.176515	127.79	90.966	5	19	12	6	7.5
N15	0.000233	2.425	432.007	791	954	30	30	850.9	O21	0.063414	77.929	974.447	50	98	300	300	53.2
N16	0.000239	2.499	445.606	786	952	30	30	843.7	O22	2.740485	92.779	263.810	5	10	6	6	6.4
N17	0.000261	2.674	467.223	795	1006	36	36	841.4	O23	0.112438	80.950	1335.594	42	74	60	60	69.1
N18	0.000259	2.692	475.940	795	1013	36	36	835.7	O24	0.041529	89.073	1033.871	42	74	60	60	49.9
N19	0.000707	1.633	899.462	795	1021	36	36	828.8	O25	0.000911	161.29	1391.325	41	105	528	528	91.0
N20	0.000786	1.816	1000.367	795	1015	36	36	846.0	O26	0.005245	161.83	4477.110	17	51	300	300	41.0
O01	0.014355	89.830	1269.132	94	203	120	120	179.0	O27	0.234787	84.972	57.794	7	19	18	30	13.7
O02	0.014355	89.830	1269.132	94	203	120	120	120.8	O28	0.234787	84.972	57.794	7	19	18	30	7.4
O03	0.014355	89.830	1269.132	94	203	120	120	121.0	O29	1.111878	16.087	1258.437	26	40	72	120	28.
O04	0.030266	64.125	4965.124	244	379	480	480	317.4									

TABLE XX

GENERATOR DATA WITH VALVE POINT EFFECTS OF TEST SYSTEM 5

Unit_i	a_i	b_i	c_i	e_i	f_i
C05	0.042468	54.242	1976.469	700	0.080
C10	0.005063	13.226	1320.636	600	0.055
C15	0.003901	14.651	1176.504	800	0.060
C22	0.003684	14.656	1229.131	600	0.050
C33	0.003542	15.033	1074.810	600	0.043
C40	0.001581	15.815	1436.251	600	0.043
L10	0.000044	71.584	1898.415	1100	0.043
L28	0.081540	22.941	13813.001	1200	0.030
L30	0.035475	45.017	9750.750	1000	0.050
L42	0.054868	79.458	2982.219	1000	0.050
O08	0.001580	81.805	2290.381	600	0.070
O10	0.076810	46.665	6743.302	1200	0.043

TABLE XXI

PROHIBIT ZONES OF UNITS OF TEST SYSTEM 5

Generator	Zone 1	Zone 2	Zone 3
C08	[250, 280]	[305, 335]	[420, 450]
C32	[220, 250]	[320, 350]	[390, 420]
L32	[230, 255]	[365, 395]	[430, 455]
O25	[50,74]	[84, 95]	

TABLE XXII
DATA FOR TEST SYSTEM 6

$Unit_i$	P_i^{min}	F1	P1	F2	P3	F3	P_i^{max}	Fuel type	a_i	b_i	c_i	e_i	f_i
1	100			196			250	1 & 2	0.0019	-0.3059	21.1300	0.0211	-3.0590
		1				2							
2	50		114		157		230	1 & 2 & 3	0.0042	-1.2690	118.4000	0.1184	-12.6900
		2		3		1							
3	200		332		388		500	1 & 2 & 3	0.0015	-0.3116	39.7900	0.0398	-3.1160
		1		3		2							
4	99		138		200		265	1 & 2 & 3	0.0059	-2.3380	266.8000	0.2668	-23.3800
		1		2		3							
5	190		338		407		490	1 & 2 & 3	0.0011	-0.0873	13.9200	0.0139	-0.8733
		1		2		3							
6	85		138		200		265	1 & 2 & 3	0.0059	-2.3380	266.8000	0.2668	-23.3800
		2		1		3							
7	200		331		391		500	1 & 2 & 3	0.0011	-0.1325	18.9300	0.0189	-1.3250
		1		2		3							
8	99		138		200		265	1 & 2 & 3	0.0059	-2.3380	266.8000	0.2668	-23.3800
		1		2		3							
9	130		213		370		440	1 & 2 & 3	0.0006	-0.0182	14.2300	0.0142	-0.1817
		3		1		3							
10	200		362		407		490	1 & 2 & 3	0.0011	-0.0994	13.9700	0.0140	-0.9938
		1		3		2							

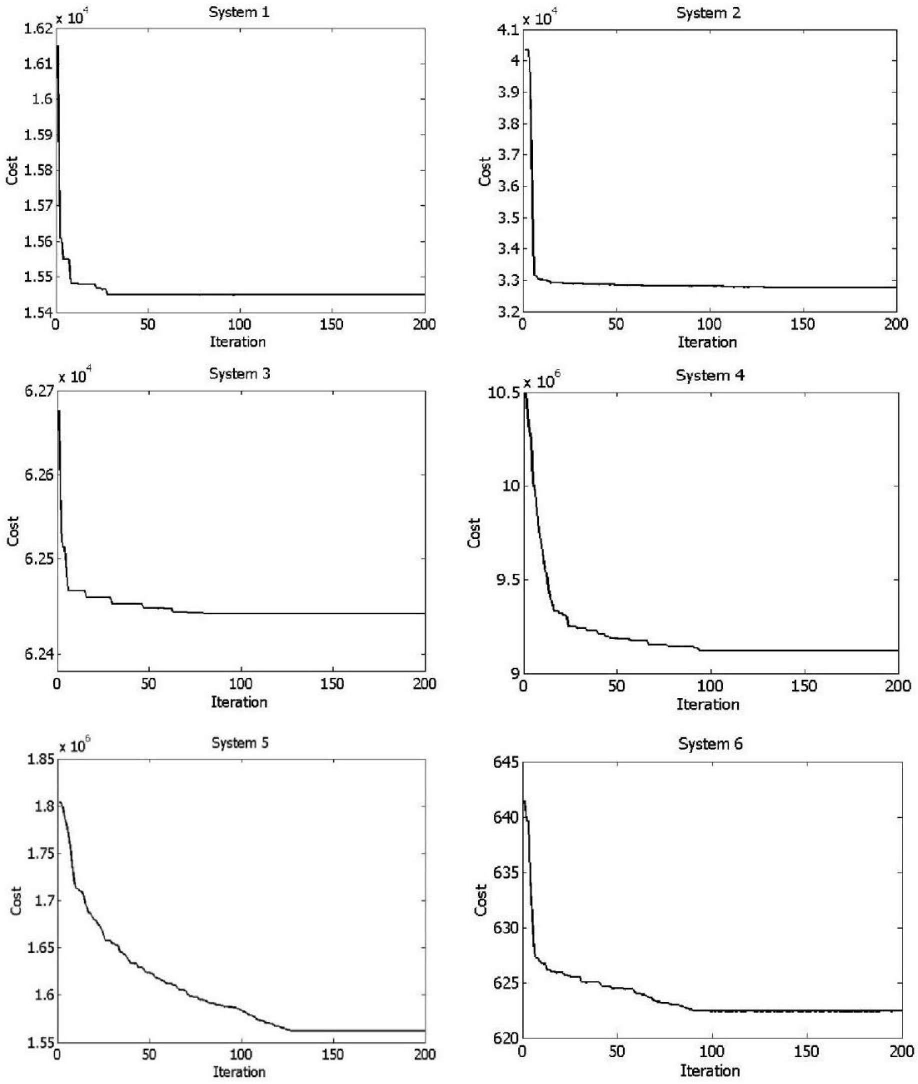

Fig. 2. Convergence diagram for six power test systems

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