A novel exclusive binary search algorithm to solve the nonlinear economic dispatch problem

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This paper introduces a new exclusive binary search (EBS) algorithm to solve the economic dispatch problem (ED). This new algorithm converges to the best possible solution, corresponding to the precision requirements of the problem with a systematic search structure. The essentia l purpose of economic dispatch is the optimal allocation of each generator's load sharing and the cost reduction of the active units in the power system. In this article, nonlinear factors and constraints are considered, including inlet steam valves' effect, Valve-Point Effect (VPE), generation and load balances in the system, prohibited operating zones (POZs), power generation limits, ramp rates limits, and line losses. According to these constraints, the complexity of computation increases. However, the proposed algorithm will be able to find the optimal solution. This algorithm is implemented on three standardized 13, 15, and 40-unit test systems considering different operating conditions. Simulation results indicate the capability of this algorithm to solve ED problems. © 2020 Journal of Energy Management and Technology

keywords: *Exclusive Binary Search, Valve-Point Effect (VPE), Prohibited Operating Zones (POZs), Economic Dispatch.*

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NOMENCLATURE

EBS Exclusive binary search
ED Economic dispatch
VPE Valve-point effect
POZs Prohibited operating zones
C Arbitrary ratio
F(P) Total fuel cost
N Number of generators
a_i, b_i, c_i Cost coefficient of the generator i
e_i, f_i Cost factors of VPE
$P_{i,min}$ Minimum output power of ith generator
P_D Total power demand
P_L Total transmission loss of the system
B Transmission loss coefficients
k Number of problem dimensions
R Maximum calculated value per loop
$P_{i,max}$ Maximum output power of ith generator
RU Ramp-up rate limit
RD Ramp-down rate limit
n Number of loops
g_k Loop number generates the first solution
$R_{n,g}$ Number of computations required in n loops to reach the stop index "ρ"
ρ Stop index (accuracy value)
$n\prime$ Number of loops
$R_{n\prime}$ Maximum number of computations
ee Value of the power generation to fulfill the equality constraints
X Proportional to add power generation value

1. INTRODUCTION

The aim of solving the problem of economic dispatch in the power system is the output planning of the power generation units in a way that the load demand for the power system is provided at the minimum possible cost. In this regard, all the equality or inequality constraints of the power system must be met. These constraints include the limitation of active power generation units, the effects of steam valves, prohibited operating zones, and transmission losses [1].

The fuel cost increasing plus the reconstruction of power grids causes considerable attention to the economic dispatch problem. This is a non-linear optimization problem in which the optimal power generation of each unit is determined in such a way that the objective function of the system, fuel cost function, is minimized.

By adding the sinus semicolon to the quadratic charge function and considering the valve-point effect, the cost function of the power generation units will have a nonlinear and non-symmetrical characteristic,which leads to be a complicated, non-invasive, and discontinuous problem. If there are multiple cost functions for generating units, the number of local minima of the problem will be very high. The issue of local optimization escape will be raised [2].

In recent years, researchers have focused on innovative and interactive methods based on artificial intelligence (AI), whereas classic and traditional methods such as linear and nonlinear programming, Landa, Gradient, and Newton have very low efficiency in solving the problem of economic dispatch [3].

In [4], Particle Swarm Optimization (PSO) is expressed. In this method, the power generation of each generator unit is considered as a particle that moves in the direction of reducing power generation costs, according to a particular pattern. Reference [5] describes a method called Two-Phase Mixed Integer Programming (TPMIP). This method consists of two steps. In the first step, the linearization and numerical programming combination for units that include VPE and POZs are performed. In the second step, compression operation is applied to the output power. This method is implemented on 13, 15, and 140 -unit test systems under different conditions, and the results have been compared with other methods. In reference [6], a search-based method called the Different Search Algorithm (DSA) is proposed to solve the optimal economic dispatch problem, which has been tested on standard systems of 9, 30 and 57- IEEE bus system. The results in this article are compared with other methods, such as Tabu Search (TS) [7], Artificial Bee Colony (ABC) [8], and Differential Evolution algorithm (DE) [9] which demonstrates the convergence and accuracy of the algorithm as well as the power to analyze it in solving the nonlinear problems of power systems. In Reference [10], the Adaptive Group Search Optimization algorithm (AGSO) applies to multi-objective ED problems. The above algorithm is tested on the 30 and 57- IEEE bus system, and thus, the convergence and accuracy of the algorithm in nonlinear objective issues and functions are presented with the goal of multi-objective optimization. In [11], a search algorithm called the Gravity Search Algorithm (GSA) is used to solve the problem of multi-objective optimal load playback. The result of its implementation on the 30- IEEE bus system is the ability to analyze the algorithm to minimize fuel costs, losses, and total emissions of greenhouse gases. In this algorithm, solutions from the searchable space are presented randomly. The fitness value of the solutions is evaluated and used as a crime for their respective solutions.

The reference [12] uses the (C-GRASP-DE) method to solve the economic dispatch considering non-uniform behavior. Therefore, it uses combining Greedy Randomized Adaptive Search Procedure (C-GRASP) [13] and Difference Evolutionary (DE). Other methods and algorithms have been proposed to optimize the economic dispatch as well as the economic dispatch of power systems. Such as Bat Algorithm (BA) [14] and Black Hole Algorithm (BHA) [15], which is usually essential in convergence, accuracy, and solution speed, and their choice depends on the type of problem and its parameters [16]. In [17], a combination of two Particle Swarm Optimization (PSO) and Synthetic Fish Algorithm (AFSA) algorithms is proposed to solve the economic dispatch problem. In this paper, nonlinear constraints and constraints are also used to solve the problem of economic dispatch.

In [18], the Improved Stochastic Fractal Search algorithm (IFSF) method is used to solve the economic dispatch problem of the standard 16-IEEE bus system and 120-IEEE bus system whit prohibited operating zones without considering losses. In this way, members of the population are distributed in the search space, and each member is divided into several new members in a random pattern but based on a repeatable geometric symmetry. This operation will generate new demographic populations and thus create uniform coverage over the search space. This strategy increases the likelihood of finding an optimal global point. As discussed in the preceding paragraphs, many methods have been proposed to solve the ED problem. In these algorithms, the accuracy of ED problem solving cannot be predetermined. To achieve the desired accuracy, the algorithm needs to be repeated several times. In this paper, a new algorithm is proposed that firstly converges to the best solution with only one execution of the algorithm. Secondly, the accuracy of the final algorithm solution can be determined.

The formulation of economic dispatch, the description of the proposed EBS algorithm, and the use of the EBS algorithm on three test systems and conclusions are presented below.

2. MATHEMATICAL FORMULATION OF THE ECONOMIC DISPATCH PROBLEM

A. The objective function

The conventional objective function for the economic load dispatch problem is to minimize the total fuel cost of generators. The F_C (cost function of power system) is function includes the cost of the power generator and the valve-point effect, as shown in relation (1):

$$F_c = \sum_{i=1}^{N} F_i(P_i) + \sum_{i=1}^{N} |e_i * \sin(f_i * (P_{i,\min} - P_i)| \tag{1}$$

In relation (1), N is the number of system generators, $F_i(P_i)$ is the total fuel cost in the ith generation unit, and e_i and f_i are the cost factors of generators to load the effect of the inlet steam valve fuel on power generators. $P_{i,min}$ is the minimum output of the ith fuel generator. The fuel cost of each unit is calculated as follows:

$$F_i(P_i) = a_i + b_i \times P_i + c_i \times P_i^2 \tag{2}$$

where $a_i, b_i, andc_i$ are the cost coefficient of the generator i [5, 19].

B. Equality and inequality constraints

In addition to the effect of the inlet steam valve, which is included in the target function, other constraints are also considered, including the rate of change in power generation, the prohibited operating zones, the power balance, and the losses of transmission lines [20].

The total power output needs to be equal to the demand plus the transmission loss. Consequently, the power balance equation must be as follows [5]:

$$\sum_{i=1}^{N} P_i - P_L - P_D = 0 \tag{3}$$

where, P_D is the total power demanded in terms of megawatts, and P_L represents the losses in the transmission lines of the system. P_L is a function of the power outputs combined with the B coefficients as follows:

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{i0} P_i + B_{00} \quad \textbf{(4)}$$

where B_{ij}, B_{i0}, and B_{00} are coefficients for calculating the transmission loss. B_{ij} is a coefficient associated with P_i and P_j. B_{i0} is related to the power output of unit i and B_{00} denotes a constant.

The inequality that is associated with the capacity of each power generation unit is considered as follows:

$$P_{i,\min} \leq P_i \leq P_{i,\max} \quad \textbf{(5)}$$

where Pi, max is the maximum power output of the ith generator.

The power output of unit i is affected by its ramp rate constraints. The generator may increase or decrease its power generation according to the corresponding permissible range. This constraint is expressed for each unit as follows:

$$\max\left(P_{i,\min}, RU_i - P_i\right) \leq P_i \leq \min\left(P_{i,\max}, P_i^0 - RD_i\right) \quad \textbf{(6)}$$

where RU_i and RD_i are the ramp-up and down rate limits of unit i, respectively, and P_i^0 is the generator's power generation in the output of the previous step.

Some of the generators have special prohibited operating zones. The POZs constraints can be described as follows:

$$P_i \in \left\{ \begin{array}{l} P_{i,\min} \leq P_i \leq P_{i,1}^{i} \\ P_{i,k-1}^{u} \leq P_i \leq P_{i,k}^{l}, k = 1, ..., zo_i \\ P_{i,z_i}^{u} \leq P_i \leq P_{i,\max} \end{array} \right\} \quad \textbf{(7)}$$

In this equation, $P_{i,k}^{l}$ and $P_{i,k}^{u}$ are up and down boundary limits of the kth generator prohibited zone.

3. INTRODUCING THE EXCLUSIVE BINARY SEARCH ALGORITHM (EBS)

The main idea of this algorithm is the interval division operation in the binary algorithm [20, 21] and the convergence toward the solution. The goal of the binary search algorithm is to find a specific value (target) from a set of different array values. This algorithm does not compare individual arrays to find the target. The strategy of this algorithm is to first arrange the arrays in descending order. It then compares the target with the median value of the ordered array, and if the target is larger (or smaller), it removes half of the search space and again mediates the remaining space and performs the comparison again. This will continue until the target position in the array is reached. This algorithm applies to discrete data. This algorithm has a high convergence speed to find the target. In the ED problem, data and constraints on the power system are continuous. The binary search algorithm mentioned in [20, 21] has been designed only for problems with discrete data. Therefore, this algorithm isn't suitable for the ED problem. This limitation will has an adverse effect on the real power system results. But, the proposed algorithm is designed to remove the parts of the continuous search space where it is less likely to find better solutions. Also, the best solution obtains according to the specified accuracy and it can update.

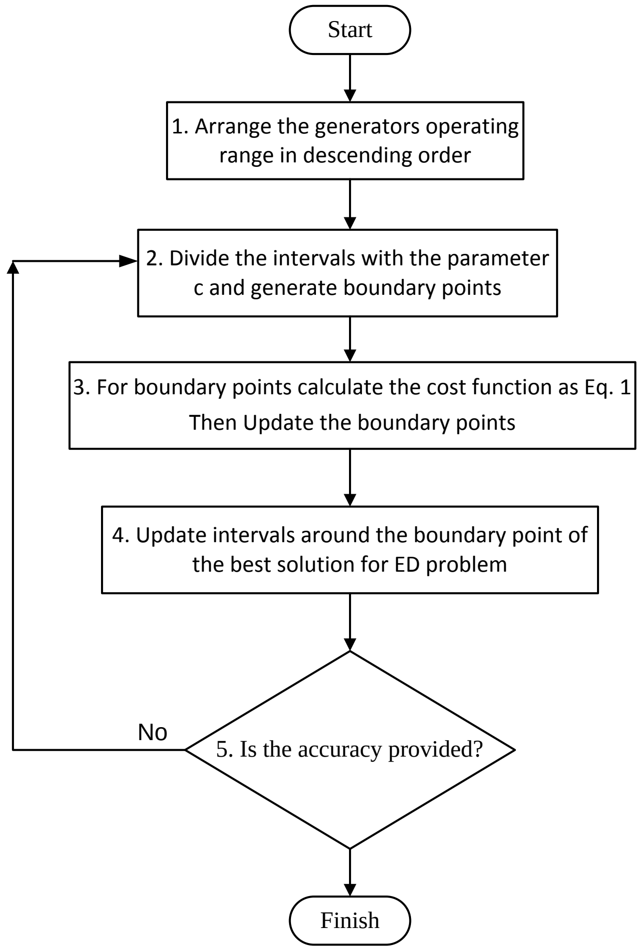
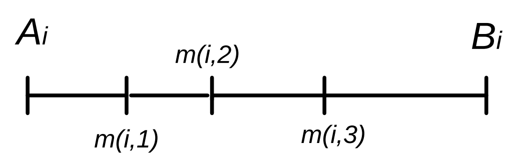


Fig. 1. The flowchart of the EBS algorithm.



A. Algorithm description

The flowchart and steps of the proposed EBS algorithm are presented in Fig. 1.

Step 1: The intervals, which are inequality (constraints on the power output of each generator) are arranged in descending order.

Step 2: Each interval with arbitrary ratios of C1, C2, and C3 (That: 0<C1+C2+C3<1 and C1, C2, C3>0) is divided into four sections, and the boundary points are determined as follows:

$$\left\{ \begin{array}{l} m_{(i,1)} = (B_i - A_i) \times C_1 \\ m_{(i,2)} = m_{(i,1)} + (B_i - A_i) \times C_2 \\ m_{(i,3)} = m_{(i,2)} + (B_i - A_i) \times C_3 \end{array} \right. \quad \textbf{(8)}$$

Where A_i and B_i are the minimum and maximum power outputs of unit i, respectively. Therefore, for k generator, 3k is the boundary point. In the second loop of the algorithm, the values are considered: C1=C2=C3=0.25 (For uniform sampling)

Step 3: According to the loop below the values of the objective function (cost function of power system) is calculated for 3k boundary points to determine the best solution:

If (B1-A1) > (Acceptable Range of Percent Error)
for j_1=1 to 3
for j_2=1 to 3
⋮
……… for j_k=1 to 3
…… $min[f(m(1,j_1), m(2,j_2), \ldots, m(k,j_k))+$
$abc(\sum_{i=1}^{k} m(i,j_i) - P_D - P_L)]$
……… end
⋮
…… end
… end
end

Step 4: Updates boundaries. In the formation of the new boundary, the point of the left and right boundaries around the best solution from stage 3, will be the criterion of the new boundary. So that the inequality constraints are supplied. In the ED problem, the generator output power limit is updated. Generators are only allowed to generate power in these ranges.

Step 5: If the solution is not provided accuracy, go to step 2 Go to Step 2 if the balance of power generation and power demand is provided, but the solutions are not yet accurate.

Step 6: Finish

The stop index (the accuracy value) can be determined by a number such as ρ, as a percentage by the user, which expresses the amount of the major deviation percentage for each interval. Therefore, Acceptable Range of Percent Error (ARPE) is as follows:

$$ARPE = \frac{\rho}{100}(B_i - A_i) \quad (9)$$

In this algorithm, the following equations can be expressed to quantify and predict the state of the solutions:

$$R = 3^k \quad (10)$$

where R is the maximum number of computations per loop.

$$n = round\left[\frac{\ln(\frac{100}{\rho})}{\ln(2)}\right] \quad (11)$$

where n is the number of loops needed to reach the ARPE.

$$R_n = n \times 3^k \quad (12)$$

where R_n is the maximum number of computations in n loops to reach the optimal solution.

In Fig. 2, the relation between the maximum number of calculations (R_n) and the accuracy of the algorithm (ρ) is calculated from 0.0001 to 0.01 for an ED problem up to 40 generators (k) is plotted.

According to Eqs. (11) and (12), it is clear that, as to accuracy increases, the number of computations needed to produce the best solution will increase.

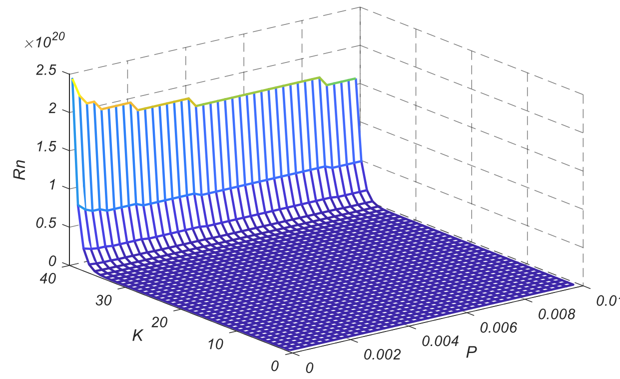


Fig. 2. The relation between R_n, ρ, and k.

B. Constraints problem provision

Typically, ED issues are considered both equality and inequality constraints. It is not possible to provide equality constraints while running the algorithm. These constraints are implicitly included with the inequality constraints in the algorithm. However, the final solution is acceptable when equality constraints are also met. Therefore, a strategy should be put in place to ensure equal coverage of the ED problem. There are generally two situations. The first involves issues where no transmission losses are considered. In this case, the amount of power deficit to provide the equation (ee) is as follows (for N generators):

$$ee = P_D - \sum_{i=1}^{N} P_{i,old} \quad (13)$$

Therefore, to compensate for this, it is recommended to increase the output of each generator according to the following equation:

$$x = ee \Big/ \sum_{i=1}^{N} P_{i,old} \quad (14)$$

$$P_{i,new} = P_{i,old} + x \times P_{i,old} \quad (15)$$

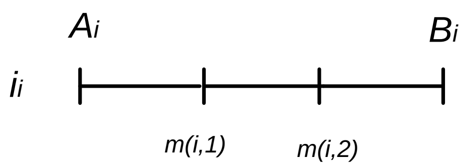
Where $P_{i,old}$ is the amount of output power of each generator that obtained from the output of the algorithm, and $P_{i,new}$ is the amount of output power of each generator in the modified state to provide equality constraints. Provided that there are no violations from other constitutions of the issues.

The second situation relates to the issues in which transmission losses are considered. Because of the dependence between the losses and generator power, it is suggested to calculate the percentage increase x for each generator from the following equation. Provided that there are no violations from other constitutions of the issues:

$$P_D + P_L - \sum_{i=1}^{N} P_{i,old} = ee \quad (16)$$

$$H = \sqrt{[(\sum_{i}^{N} P_{i,old}(B_{i0} - 1))^2 - 4 \times (\sum_{i}^{N}\sum_{j}^{N} P_{i,old} B_{ij} P_{j,old})(ee + B_{00})]} \quad (17)$$

$$x = [-(\sum_{i=1}^{N} P_{i,old}(B_{i0} - 1)) - \frac{H}{2 \times \sum_{i}^{N}\sum_{j}^{N} P_{i,old} B_{ij} P_{j,old}}] \quad (18)$$



C. Increasing convergence rate of the algorithm

Two strategies are suggested to increase the convergence rate of the algorithm to achieve the optimal solution:

A) Determine the solution precision as a percentage of the range of the largest constraint (The largest power generation limit of generators available in the power system). The acceptable range of percent error is as follow:

$$ARPE = \frac{\rho}{100}(B_1 - A_1) \tag{19}$$

$$g_k = round\left[\frac{\ln(\frac{100}{\rho \times L_k})}{\ln(2)}\right] \tag{20}$$

$$L_i = \frac{B_1 - A_1}{B_i - A_i} \quad , \quad (i = 1, 2, ..., k) \tag{21}$$

Where A_1 and B_1 are the minimum and maximum power outputs (intervals) of unit 1, respectively. Also, k is the smallest index, and index 1 is the largest interval in the problem.

Moreover, if the intervals are not equal, the first acceptable solution is obtained in the K interval range. This solution is obtained in gKth loop ($g_k < n$).

$$R_{n,g} = \frac{3^k}{3}(2g_k + n) \tag{22}$$

Where $R_{n,g}$ is the number of computations needed in the n loop to reach the stop index ρ. However, applying this strategy will reduce the accuracy of the algorithm.

B) Reduce the number of boundary points in the intervals (reduce the number of boundary points sampling).

In this case, instead of using three points for dividing the intervals into 4 parts, they were converted to 3 parts by the ratio C = 1/3, equal to the two boundary points $m_{i,1}$ and $m_{i,2}$.

$$\begin{cases} m_{(i,1)} = (B_i - A_i) \times C \\ m_{(i,2)} = m_{(i,1)} + (B_i - A_i) \times C \end{cases} \tag{23}$$

So we will have 2k boundary points. In this case, a maximum of n' loops is required to achieve the desired stop index ρ:

$$n' = round\left[\frac{\ln(\frac{100}{\rho})}{\ln(\frac{3}{2})}\right] \tag{24}$$

As a result, the convergence speed of the algorithm to achieve the desired accuracy will be "$(0.7/0.4) * (2.3)^k$" OR "$1.75 * (1.5)^k$".

D. Enhance the performance of the algorithm

To improve the solutions during the algorithm implementation, it is recommended to use the constant coefficients C independently for each interval. It is possible to improve the quality of the algorithm's performance in solving the ED problem by choosing appropriate values of the boundary points in the parts of the search space that are likely to better solutions. This item is usually applicable in cases where records and statistics are available on the operation of generators.

4. IMPLEMENTATION OF EBS ALGORITHM ON THE ECONOMIC DISPATCH OF THE STANDARD TEST SYSTEMS

For validation of the effectiveness of the EBS algorithm, it is applied to Three IEEE standard test systems.

First Test System: Includes 13 generator units, considering the valve-point effect and without considering the losses of transmission lines [5].

Second Test System: Includes 15 generator units, regardless of the valve-point effect and considering the losses of transmission lines and prohibited operating zones [19].

Third Test System: Including 40 generator units, considering the valve-point effect and without considering the losses of transmission lines [5].

The simulation results are compared to the EBS algorithm with other previous methods. This comparison shows that, firstly, the EBS algorithm's solutions are definite, and the algorithm is executed only once to obtain the best solution, secondly, by changing the parameters of C and ρ, the optimal solution accuracy can be determined. Therefore, the proposed algorithm in this paper is better and more reliable. These simulations were performed with matlab2013 software with an Intel Core i5-4200U, 1.6 GHz processor system. In the table comparing the results of the proposed algorithm with other algorithms, only the economic value of the methods is considered. Because the processor used in the other methods mentioned in the previous methods was not the same as the processor used in this paper, no comparisons were made regarding the timing of the algorithms. However, the processing time of the proposed algorithm to get the best solution for each standard test system is mentioned.

A. First test system

The test system consists of 13 generator units with VPE and nonlinear fuel cost function. The goal is to find the output power of generators so that the minimum fuel costs can be achieved for the power system. The parameters and data of this test system are given in reference [20]. The amount of load that is demanded by the system is 1800 megawatt. The cost function and formulation of the problem are presented by Eq. (1) of this paper. The accuracy value for this test system is 0.0000025, according to Eq. (9). The comparison of results obtained for the optimal value of the cost function by the proposed method and the other methods addressed in references has been shown in Table 1. The reason for choosing this accuracy is that the proposed algorithm can provide a better solution than the references mentioned in Table 1. However, this increase in accuracy increases the running time of the algorithm. The algorithms listed in Table 1 have to run the algorithm many times to provide the best solution. This also increases the total time to solve the problem. (Papers usually refer to the one running times that produced the best solution.) Moreover, the proposed power generation for each generator is presented in Table 2. The simulation time to achieve the minimum fuel cost was 163.3 seconds.

Furthermore, the process of the algorithm's convergence to achieve the best solution is presented in Fig. 3. This figure shows the fuel cost of power generators according to the optimum points founded by the algorithm. This curve shows that the proposed algorithm improves the solutions founded for the ED problem. This process continues until it converges to the best solution. It is noteworthy that the algorithm runs only once, and the solutions are optimized during execution. The "best solution" is the one with it has the expected accuracy. That means, the

Table 1. Comparison of the results for TS1

Method	Total cost ($/h)
IFEP [22]	17,994.07
PSO-SQP [23]	17,969.93
HS [24]	17,965.62
GA-PS-PSO [25]	17,964
ST-HDE [26]	17,963.89
FA [27]	17,963.83
DSD [28]	17,963.8292
SSA [29]	17,963.76
EBS	**17,963.81**

Table 2. Output power for each generator for TS1

Unit	Generation (MW)	Unit	Generation (MW)
1	628.3161	8	109.8681
2	149.5982	9	109.8671
3	222.7481	10	40.0006
4	109.8681	11	40.0001
5	60.0004	12	55.0005
6	109.8641	13	55.0002
7	109.8681		

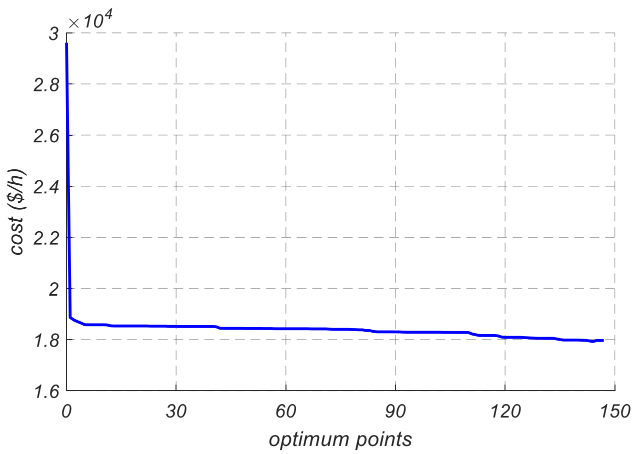


Fig. 3. The algorithm's convergence for TS1.

best solution is when: $B'i - A'i < ARPE$ for this case study, $ARPE = [25/(10^9)] * (Bi - Ai)$. $B'i$ and $A'i$ are the upper and lower limits of the new intervals. As shown in Fig. 3, and also in Sub-section B, the algorithm compensates for the difference between the power demanded (PD) and total output power ($\sum_{i=1}^{n} P_i$) after finding the best solution, which compensating this amount will increase the cost, and it is shown in Fig. 4 in more detail. In this figure, at the end of the convergence, the curve has a mutation (ramp). Because the algorithm calculates the cost function considers the load balance constraint between the generated power and the power demand while it has a very small mismatch. So the cost of this mismatch which is depending on the ρ. The proposed algorithm adds it to the final cost.

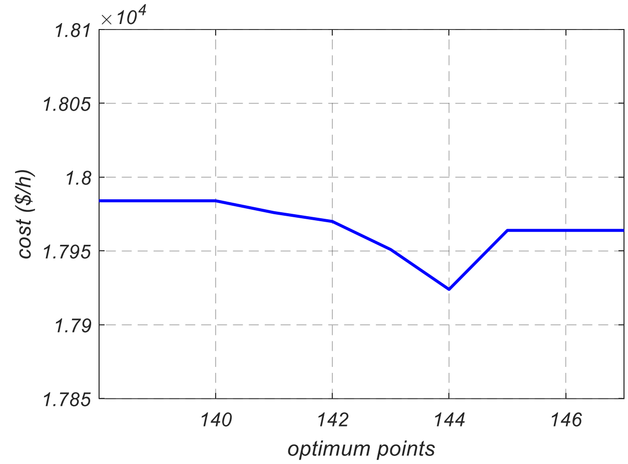


Fig. 4. Changes in the final cost for TS1.

Table 3. Comparison of the results for TS2

Method	Total cost ($/h)
FAPSO [30]	32659.794
PSO [30]	32858
GA [31]	33063.54
DE [31]	32588.865
SPSO [32]	32798.69
SA [33]	32786.4
APSO [34]	32732.77
CSO [33]	32588.918
ACSS [35]	32678.129
EBS	**32554**

B. Second test system

This test system consists of 15 generator units, including the losses of transmission lines and the nonlinear fuel cost function and prohibited operating zones, regardless of VPE. The goal is to find the output power of generators so that the minimum fuel costs can be achieved for the power system. The parameters and data of this test system are given in reference [4]. The demand for this system is 2630 megawatt. To solve this ED problem, the precision is equal to 0.00001, according to Eq. (9) by using the EBS algorithm. The obtained results show the optimal value of the cost function, and its comparison with the other methods is presented in Table 3. Moreover, the proposed power generation for each generator is shown in Table 4. The simulation time to achieve the minimum fuel cost was 216.5 seconds.

Moreover, the convergence process of the algorithm is presented in Fig. 5 to achieve the best solution.

As shown in Fig. 5, and also in Sub-section B, The algorithm, after finding the best solution, compensates for the difference between the power demanded (PD) and the loss (PL)of the total generated power ($\sum_{i=1}^{n} P_i$) which compensates for this increase in cost, which is shown in Fig. 6 in more detail. It has a mutation (ramp). Its reason is as like as mentioned in the first test system.

Table 4. Output power for each generator for TS2

Unit	Generation (MW)	Unit	Generation (MW)
1	454.3152	9	25.0174
2	455	10	31.2915
3	129.0896	11	76.7546
4	130	12	80
5	233.964	13	26.0181
6	460	14	15.0104
7	464.3221	15	16.0111
8	60.0417		
Transmission loss (MW)=26.8356			

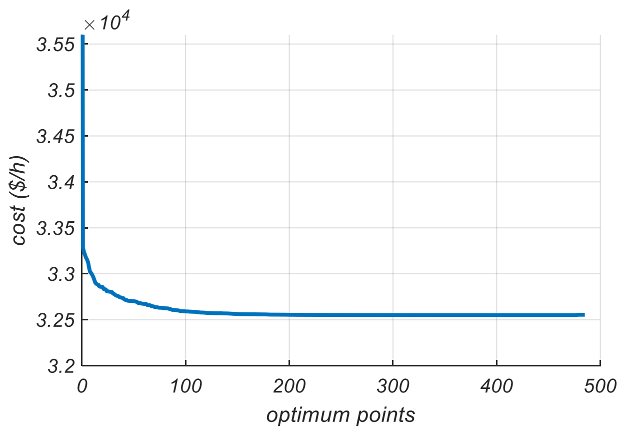


Fig. 5. The algorithm's convergence for TS2.

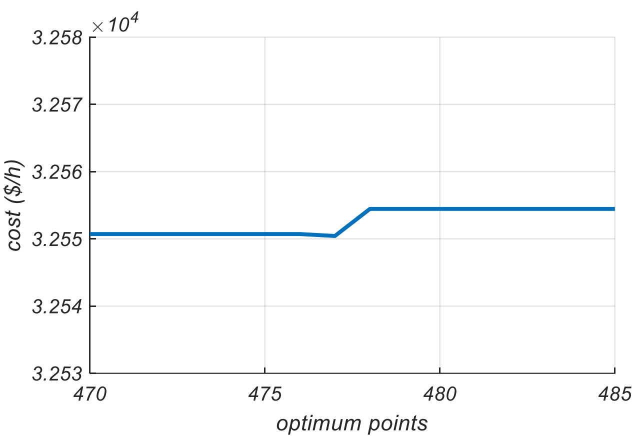


Fig. 6. Changes in the final cost for TS2.

Table 5. Comparison of the results for TS3

Method	Total cost ($/h)
IFEP [22]	122,624.35
(POZ1) PSO [30]	123,861.45
(POZ2) PSO [30]	124,875.3706
AA [36]	121,788.7
NAPSO [30]	121,412.62
EBS	**121,412.6**

Table 6. Output power for each generator for TS3

Unit	Generation (MW)	Unit	Generation (MW)	Unit	Generation (MW)
1	110.6998	15	394.2789	28	10.0018
2	110.7998	16	394.2778	29	10.0028
3	97.4998	17	489.2787	30	87.7998
4	179.7498	18	489.2788	31	189.9998
5	87.7988	19	511.2788	32	189.9998
6	139.9998	20	511.2789	33	189.9998
7	259.6008	21	523.2789	34	164.7998
8	284.6008	22	523.2787	35	199.9998
9	284.5898	23	523.2787	36	194.3978
10	129.999	24	523.2788	37	109.9978
11	94.0008	25	523.2789	38	109.9988
12	94.0008	26	523.2787	39	109.9978
13	214.7598	27	10.0008	40	511.2798
14	394.2778				

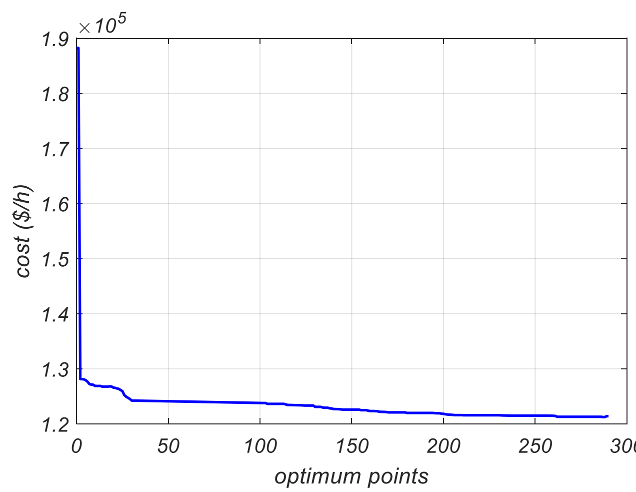


Fig. 7. The algorithm's convergence for TS3.

C. Third test system

This test system consists of 40 generator units, considering the VPE and the nonlinear fuel cost function. The goal is to find the output power of generators so that the minimum fuel costs can be achieved for the power system. The parameters and data of this test system are given in reference [5]. The demanded load is 10500 megawatts. To solve this problem, the accuracy value for this test system is 0.0000025, according to Eq. (9). The obtained results show the optimum cost function and its comparisons with other methods are shown in Table 5. Furthermore, the output power for each generator unit in this test system is indicated in Table 6. The simulation time to achieve the minimum fuel cost was 531.5 seconds.

Moreover, the convergence process of the algorithm is presented in Fig. 7 to achieve the best solution.

As shown in Fig. 7, and also in Sub-section B, The algorithm compensates for the difference between the power demand (*PD*) and total output power ($\sum_{i=1}^{n} P_i$) which compensates for this in-

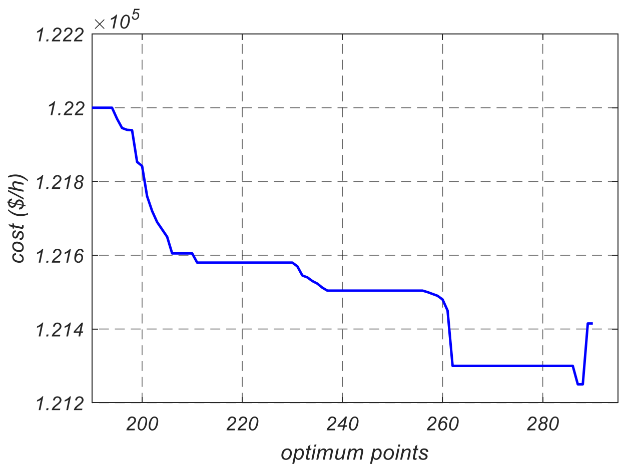


Fig. 8. Changes in the final cost for TS3.

crease in cost after finding the best solution, which is shown in Fig. 8 in more detail. It has a mutation (ramp). Its reason is as like as mentioned in the first test system.

5. CONCLUSION

In this paper, a new EBS algorithm was proposed to solve the economic dispatch problem. In order to clarify the conditions of the ED problem, the factors and nonlinear constraints, such as the VPE, the power generation and power demand balance in the system, the POZs, the power generation limits, and the losses of transmission lines were considered. In order to increase the efficiency of the proposed algorithm, several methods were presented to increase the convergence rate, and the complexity of the calculations was analytically evaluated in each case. Another advantage of the proposed method, compared with other methods presented in the articles, is the certainty of the results and one-time execution of the algorithm. Moreover, it is possible to determine the accuracy of the optimal solution by changing the parameters of C and ρ, which is more reliable than the mentioned methods in the references. The evaluations for different standard test systems and the comparison of results with previous algorithms confirm the capability of the proposed algorithm to find a better solution.

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