



## A Proposed Improved Hybrid Hill Climbing Algorithm with the Capability of Local Search for Solving the Nonlinear Economic Load Dispatch Problem

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### ABSTRACT

This paper introduces a new hybrid hill-climbing algorithm (HHC) for solving the Economic Dispatch (ED) problem. This algorithm solves the ED problems with a systematic search structure with a global search. It improves the results obtained from an evolutionary algorithm with local search and converges to the best possible solution that grabs the accuracy of the problem. The most important goal of economic load dispatch is the optimal allocation of each generator's contribution to provide the load and reduce the costs of active units in the power system. This is generally due to presence of the nonlinear factors and limitations, such as the effect of the steam inlet valve (valve point effect (VPE)), the balance between the power generation and power demand of the system, the prohibited operating zones (POZS), power generation limits, ramp rate limits, and transmission losses. This algorithm is implemented on three 13-unit, 15-unit and 40-unit test systems with different operating conditions, and also for the same three test systems in combination with the evolutionary PSO algorithm. The simulation results show the efficiency of the proposed algorithm in solving ED problems.

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## 1. INTRODUCTION

The increase in fuel costs and the reconstruction of power grids have made the economic dispatch problem as an important subject. The purpose of the economic dispatch problem in the power system is to plan the generation units in a way that the load demand for the power system is provided at the lowest possible cost. So, all of the constraints of the power system must be fulfilled. These constraints include the active power limitation of generator units, transmission losses, the valve-point effect, and prohibited zones [1].

This is a nonlinear optimization problem in which the optimal power generation of each unit is determined in such a way that the objective function of the system, which is the same as the fuel cost function, is minimized. By adding a sinus term to a quadratic cost function and considering the effect of the valve point effect, the cost function of the generation units would have nonlinear

and non-symmetric characteristics. This makes the problem search space complex, uneven and discontinuous [2]. The Classical and traditional methods such as linear and nonlinear programming, Landau, Newton, and the other methods are not powerful in solving the economic dispatch problem for real power networks [3].

In [4], a search-based method, "the Differential Search Algorithm (DSA)", is used for solving the economic dispatch which is tested on 9, 30, 57- bus IEEE standard systems. In this paper, the results are compared with other methods such as Artificial Bee Colony (ABC) [5], and the Differential Evolution algorithm (DE) [6]. They demonstrated the convergence and accuracy of the algorithm and also its analysis power in solving nonlinear power systems.

In [7], the Two-Phase Multiple Integer Programming (TPMIP) method is used. This method includes two stages. In the first stage, the linearization and numerical

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programming combination are performed for units that contain VPE and POZs. In the second stage, the compression operation of the range is applied to the output power. This method is implemented on 13-units, 15-units, and 40-units test systems with different conditions and the results are compared with the other methods. In [8], the Adaptive Group Search Optimization Algorithm (AGSO) is used to multi-objective ED problems. This algorithm is tested on the 30 and 15-bus systems to validate the convergence and accuracy of the algorithm in problems with nonlinear objective functions.

In [9], the (C-GRASP-DE) method has been discussed to solve the economic load dispatch problem with non-uniform behavior by combining two Differential Evolution (DE) and Continuous Greedy Random Access Search (C-GRASP) algorithms. Other innovative algorithms and methods have been proposed to optimize the load dispatch and also the economic load dispatch of power grids. Such as the Black Hole Algorithm (BHA) [10] and Bat Algorithm (BA) [11] which are usually important in the convergence, accuracy, and response rate, and their selection depends on the type of problem and its parameters [12].

A search algorithm called the Gravity Search Algorithm (GSA) has been used to solve the optimal multi-objective load dispatch problem. It minimizes the fuel costs, the transmission losses, and the total emissions of greenhouse gases [13].

Due to the presence of a sinusoidal term caused by the VPE and transmission losses, the ED problem will have a non-linear behavior. The proposed algorithm is designed to be independent of the form and cost function behavior and able to solve this nonlinear problem. The rest of this paper is organized as follows. The economic load dispatch is formulated in Section II. Then, the proposed HHC problem is discussed in Section III. In Section IV and Section V, the HHC algorithm is implemented on three testing systems independently with the capability of global search and also in combination with another evolutionary algorithm with the capability of local search. Finally, the conclusion is presented in the last section.

## 2. MATHEMATICAL FORMULATION OF THE ECONOMIC DISPATCH PROBLEM

**2.1. Objective Function** The objective function for the problem of economic load distribution is to minimize the total fuel costs of generators. The  $F_c$  function that includes the cost of the power plant and the effect of the valve point effect is considered as shown in Equation (1):

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

In Equation (1),  $N$  is the number of generator units,  $F_i(P_i)$  is the total fuel cost in the  $i$ th generator unit,  $f_i$  and  $e_i$  are the cost factors of generators for the reflection of the valve point effect of power generators.  $P_{i,min}$  is the minimum output of  $i$ th generator, the fuel cost of each unit is calculated according to the following equation:

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

which  $a_i$ ,  $b_i$  and  $c_i$  are the cost factors of the  $i$ th generator. The sinus term has been added to consider the valve point effect [14].

**2.2. Equality and Inequality Constraints** In addition to the valve point effect which included in the objective function, other constraints such as power generation constraints, ramp rate limits, the prohibited zones, the power balance, and the transmission losses are also considered [15].

**2.3. Power Balance Equation** The total power output should be equal to the demand plus the transmission losses. Therefore, the power balance equation should be as follows:

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

In this equation,  $P_D$  is the total demand power in megawatts and  $P_L$  indicates the amount of the losses in the transmission lines of the power system.  $P_L$  indicates the transmission line losses (in MW) that are determined through  $B$  coefficients, given by:

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

where the  $B$  coefficients, including  $B_{ij}$ ,  $B_{i0}$ , and  $B_{00}$ , are used to calculate the transmission losses. The power output of each unit has its lower bound and upper bound as follows:

$$P_{i,max} \leq P_i \leq P_{i,min} \tag{5}$$

which  $P_{i,max}$  is the maximum output of the generator  $i$ .

**2.4. Ramp Rate Limits** This constraint, practically limits the online performance of the units and the immediate regulation of the output power, instantly. Therefore, the generator may increase or decrease its power output based on the corresponding permissible rate. This constraint is expressed as the following for each unit which  $UR_i$  and  $DR_i$  are the up and down ramp rate limits and  $P_i^{t-1}$  is the generator production in the previous step's output:

$$\max(P_{i,min}, P_i^{t-1} - UR_i) \leq P_i \leq \min(P_{i,max}, P_i^{t-1} + DR_i) \tag{6}$$

**2.5. Prohibited Operational Zones Limitation** Due to several factors such as the limitation of the machine components, the valve point effect, vibration in

the bearing axis and so on, it can be impossible to operate the generators in some operational zones. This constraint can be expressed as:

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

In this regard,  $P_{i,k}^l$  and  $P_{i,k}^u$  are the upper and lower bounds of the  $k^{\text{th}}$  area of the generator's prohibited zones.

### 3. INTRODUCING THE HYBRID HILL CLIMBING ALGORITHM (HHC)

The proposed HHC algorithm is obtained by combining the properties of two algorithms, Iterative Deep Search (IDS) and Hill Climbing (HC) [16]. First, the HC and IDS algorithms are explained briefly and then the HHC algorithm will be expressed.

The IDS algorithm is a search-based algorithm which explores search space linearly, to a certain depth to find the desired target. In every repetition time of the searching process, the search factor explores the certain depth of the searching space and in case of not finding the desired target, it expands the depth to reach the desired target or the boundary of allowed search space. This algorithm is a repetition based algorithm. The main weakness of this algorithm for being applied in ED problems is that the optimal value of the objective function is not clear before the beginning of the search process. Because the purpose of solving an ED problem is to find the minimum value of the cost objective function on the condition of the fulfillment of the constraints. However, in the IDS algorithm, the value of the target needs to be cleared at the beginning of the operation. Therefore, this algorithm cannot be used in ED problems [16, 17].

In the Hill-Climbing algorithm (HC), search factor starts exploration process from a part of the search space to find the peak (extreme point): first, it calculates the value of the objective function in the current point, then with one step forward movement, it obtains the value of the objective function at the neighbor point. If the calculated value is less or equal to the previous value, the search factor is allowed to fix its position at a new point. This process continues until the peak (maximum value of the objective function) is found. The search factor declares that a peak has been found if the value of the objective function in one position is greater than the value of the objective function in the previous position and the next position (neighbor points). This type of implementation of the hill-climbing operation is called the maximum finder (peak finder) hill-climbing algorithm ( $HC_{max}$ ). If the above process is reversed, the factor searches for a point (position) with less than the current value. In this case, it is called a minimum finder

(hole finder) hill climbing ( $HC_{min}$ ). In both cases of hill climbing, the most important challenge is to get caught in the local extreme points and exit from it. Scenarios like random restart, throwing the factor into the other parts of the search space is suggested to resolve this weakness but sometimes due to the waste of the parts of the search space. This random nature makes them unreliable and we need to repeat the algorithm over and over again [18, 19]. In the proposed Hybrid Hill Climbing Algorithm (HHC) all weaknesses are solved.

#### 3. 1. Algorithm Description

It is assumed that the problem is to find the minimum value of the objective function. In this algorithm, two search factors, IDS and HC, provide the final solution with their cooperation. First, the hill climber search factor explores the search space systematically to find the first minimum point of the objective function. After finding it (which it could be a local extreme), it is given to the IDS auxiliary search factor. This factor starts exploration from the other side of the search space in order to find a value of the objective function which is equal or less than the value that is declared by the  $HC_{min}$  search factor. In case of finding this value, it declares the position of the  $HC_{min}$  search factor as local extreme. In this case, hill climber search factor changes its behavior from the  $HC_{min}$  state to the  $HC_{max}$  state and continues exploration process in the search space. This process is being repeated until the exploration of the whole search space and declaration of the global extreme value. Movement step for exploring the search space is determined by the  $\rho$  parameter which in this paper, it is defined as L percent of each range and proposed for the generators' production in the power system:

$$\rho_i = \frac{L}{100} (P_{imin,i,max}) \quad (8)$$

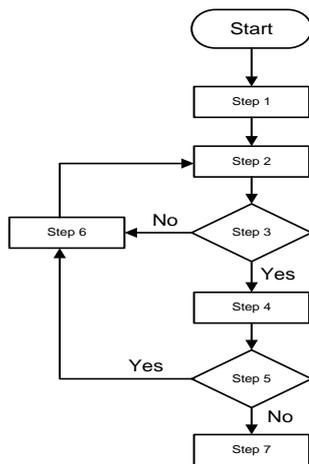
The smaller amount of the  $\rho$ , causes the solutions to become more accurate. The flowchart and the algorithm of the proposed method are as follows (see also Figure 1):

**Step 1:** Receive the problem constraints and objective function and consider a very bad solution and put it in the variable "S".

**Step 2:** Run the HC Algorithm; (For the ED problem, at this step, the search agent starts the local search by running the HC algorithm above the allowed generators' power capacity limit. This factor seeks to minimize the value of the fuel cost function of the ED problem. The first stop point of the search agent will be a local optimal value.)

**Step 3:** Is the solution obtained from HC better than "S"? (If the solution of the HC algorithm is less than the initial value of "S", it will replace "S".)

**Step 4:** Run the IDS Algorithm to find a better solution and in case of finding it, put it in the variable "S" (For the ED problem, at this step, another search agent starts the search by running the IDS algorithm of the



**Figure 1.** The flowchart of the proposed method

power generation limits. This factor has the task of finding the first values of the generated power, where the value of the problem fuel cost function is less than or equal to the value of "S".)

**Step 5:** Has local optimum occurred & search space is not complete yet? (At this step, if the cost function value is found after the IDS algorithm is executed, then the locality of the "S" solution to the HC search agent is declared.)

**Step 6:** Reverse the HC; (At this step, after confirming the locality of the "S" solution, the search agent must release itself from the local optimal state (That is, from  $HC_{min}$  to  $HC_{max}$  or reverse). To do this, the process of reversing the HC algorithm progresses and the search agent starts local search within the permitted range of generator units to find the maximum value of the ED problem cost function.)

**Step 7:** Print the HC solution; (At this step, after repeating the above steps and after completing the search on the ED problem, the best solution is declared as global optimum. In this case, the power output of the generator units will be determined for the minimum fuel cost.)

In the following, some methods are presented to increase the algorithm's convergence.

### 3. 2. Characteristics of the HHC Algorithm

- 1- Solving the problem of getting caught in the local extremes impasse, by combining two factors,  $HC_{min}$  and  $HC_{max}$ .
- 2- There is no need to determine the random parameters.
- 3- Increasing the accuracy of the problem solving just by determination of one parameter of  $\rho$ ;
- 4- Systematic searching of the search space and sampling according to a non-random special pattern;
- 5- Possibility of the implementation of the linear and nonlinear objective functions.

**3. 3. Fulfillment of the Problem Constraints** In the ED problems, equality and inequality constraints are

usually considered. Since the fulfillment of the equality constraints is impossible during the implementation of the algorithm, these constraints are implicitly considered along with inequality constraints and the best solution is presented. But the final solution is acceptable if the equality constraints are fulfilled. Therefore, a strategy should be used to fulfill the equality constraints of the problem. In this case, two situations can be discussed. The first situation is related to the problems in which no losses are considered in them. In this case, the deficit value of the power to fulfill the equality constraints ( $ee$ ) is as follows:

$$P_D - \sum_{i=1}^N P_{i,old} = ee \quad (9)$$

Therefore, to compensate this value, it is recommended to add production value, proportional to the  $x$  percent, according to the following equation:

$$x = ee / \sum_{i=1}^N P_{i,old} \quad (10)$$

$$P_{i,new} = P_{i,old} + x \cdot P_{i,old} \quad (11)$$

In which  $P_{i,old}$  is the generated power of each generator which is obtained from the algorithm solution, and  $P_{i,new}$  is the generated power of each generator in the reformed state for fulfilling the equality constraint, provided that it does not violate the other constraints of the ED problem.

The second situation is related to the problems in which the losses are not considered in them. In this case, considering the dependency of the losses and the generated power of the generators, it is recommended to calculate the increment percentage of the  $x$  according to the following equation, provided that it does not violate the other constraints of the problem:

$$P_D + P_L - \sum_{i=1}^N P_{i,old} = ee \quad (12)$$

$$H = \sqrt{[(\sum_{i=1}^N P_{i,old}(B_{i0} - 1))^2 - 4 \times (\sum_{i=1}^N \sum_{j=1}^N P_{i,old} B_{ij} P_{j,old})(ee + B_{00})]} \quad (13)$$

$$x = \frac{[-(\sum_{i=1}^N P_{i,old}(B_{i0} - 1)) - H]}{2 \times \sum_{i=1}^N \sum_{j=1}^N P_{i,old} B_{ij} P_{j,old}} \quad (14)$$

**3. 4. Increasing the Algorithm Speed** To increase the speed of the algorithm's convergence to achieve the optimal solution, two strategies are suggested:

A) Run the algorithm twice on the problem: in this strategy, at first run, with the survey step of search space,  $\rho' = m * \rho$  (where  $m$  is the step mutation), the range of the optimal solution is found and then it converges to the optimal solution with the main step of  $\rho$  in the range of  $\rho'$  by the re-execution of the algorithm. In this case, the convergence speed becomes  $m^k$  times larger and time complexity of convergence is from the following order:

$$o[(((dk^k min_{max} \quad (15)$$

In which,  $k$  is the number of problem dimensions,  $d_{min}$  and  $d_{max}$  are the first and the end of the biggest bound of the search space. In order to increase the convergence speed, the number of algorithm implementations on the problem can be increased.

B) Remove the repetitive searched space: in this strategy, the searched space by a factor is removed from the other search factor, it means that the part of the search space which is surveyed by the HC factor, is removed from the IDS factor's search space.

### 3. 5. Using HHC Algorithm in the Local Search

HHC algorithm can be used as a local searcher to improve the obtained solution of another evolutionary algorithm. For this purpose, first, the desired evolutionary algorithm (for example PSO [4]) is implemented on the ED problem and then the obtained solutions are given to the HHC algorithm as start points. The HHC search agent should start searching for operation from the desired point to the search space boundaries based on the desired accuracy. In this case, two strategies are proposed. First, the local search operation can be only continued until the first better solution is achieved (which in this case the HHC search factor does not need IDS search factor).

Secondly, local search operation can be done up to a certain percentage of the allowed range of the search space around the start point (in this paper, the search range is considered up to the closest boundary of the search space).

## 4. IMPLEMENTATION OF THE HHC ALGORITHM IN THE GLOBAL SEARCH MODE ON THE ECONOMIC DISPATCH PROBLEM OF THE STANDARD TEST SYSTEM

To evaluate the efficiency of the HHC algorithm, 3 IEEE standard test systems are used:

**First Test System:** includes 13 generator units with considering the valve point effect and ignoring the transmission line losses [7].

**Second Test System:** includes 15 generator units without considering the valve point effect and considering the transmission line losses and prohibited operation zones [14].

**Third Test System:** includes 40 generator units with considering the valve point effect and ignoring the transmission line losses [7].

The simulation results of the HHC algorithm is compared with other techniques and methods. This comparison shows that the results of the HHC algorithm are certain and the algorithm is run only once to get the best solution and also the accuracy of the optimal solution can be determined by changing the  $\rho$  survey step which in this paper, the proposed methods have better

and more reliable efficiency. Also, by using the first strategy of the algorithm speed increasing (A), the results rate, for example in the first test system, becomes 16 times larger and it becomes 34 times by using both A and B strategies of the algorithm speed increasing. 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 references was not the same as the processor used in this paper, no comparisons were made regarding the timing of the algorithms.

**4. 1. First Test System for HHC Algorithm** This test system includes 13 generator units by considering the VPE and nonlinear fuel cost function. The purpose of this ED problem is to find generators' output power so that the power system has a minimum fuel cost. Parameters and data of the test system are given in the reference [20] and the power demand of the system is 1800 MW. Cost function and the formulation of the ED problem are given according to Equation (1). The accuracy of the survey step for this test system is determined to be equal to 0.05. The obtained results to the optimal value of the cost function and comparison with the existing methods are given in Table 1. Also, the power generation of each generator unit is given in Table 2. The convergence curve is given in Figure 2.

As is clear in Figure 2 and also in section 3.3, the algorithm compensates the difference value between power demand ( $P_D$ ) and a total of the power generation ( $\sum_{i=1}^n P_i$ ), which this compensation causes a slight increase in the fuel cost which is determined with more details in Figure 3.

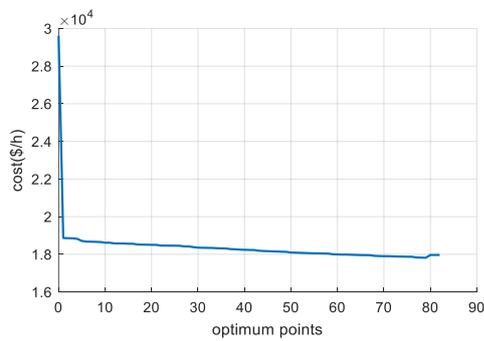
Also, for this case, speed increase strategy is used two times to run the algorithm which surveyed points of the search space, and the way of an exit from local optimum traps during the searching operation is given in Figure 4. This figure is made up of points that the algorithm has

**TABLE 1.** Comparison of the obtained results for the first test system for HHC

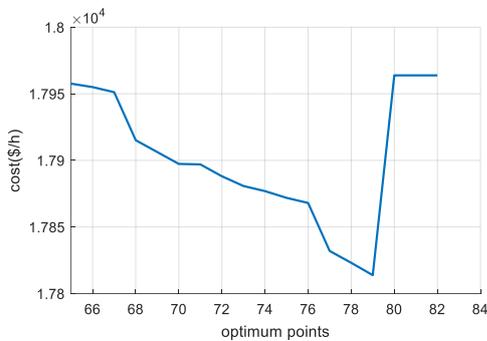
Method	Total cost ( $\$/h$ )
IFEP [20]	18,127.0600
PSO-SQP [21]	18,029.9900
HS [22]	17,986.5626
GA-PS-PSO [23]	18,199.0000
ST-HDE [24]	18,046.3800
FA [25]	18,029.1600
<b>HHC</b>	<b>17,964.0000</b>

**TABLE 2.** The power output for each generator for the first test system for HHC

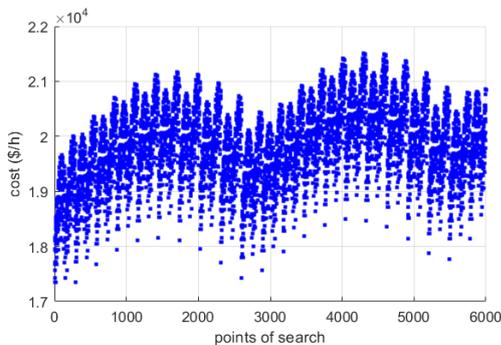
Unit	Generation (MW)	Unit	Generation (MW)
1	628.3186	8	109.8666
2	149.5996	9	109.8666
3	222.7486	10	40.0000
4	109.8666	11	40.0000
5	60.000	12	55.0000
6	109.8666	13	55.0000
7	109.8666		



**Figure 2.** The algorithm's convergence for test system 1 for HHC



**Figure 3.** Details of the fuel cost optimization in test system 1 for HHC



**Figure 4.** How to exit from local optimum traps during searching operation HHC for test system 1

calculated by considering constraints. The sinusoidal and nonlinear behavior of the cost function is quite clear. The IDS search agent causes the algorithm to don't stop at extreme points and search the entire ED search space.

**4. 2. Second Test System for HHC Algorithm**

This test system includes 15 generator units by considering the transmission line losses and nonlinear fuel cost function and prohibited zones and regardless of VPE. In this ED problem, the purpose is to find the minimum value of the fuel cost function of the generator units which is expressed in Equation (1). Data and parameters of this test system are given in reference [26]. The power demand of the test system is 2630 MW. To solve this problem using the HHC algorithm, the surveying step is equal to 0.01. The obtained results of the optimal value of the cost function and its comparison with the other existing methods are given in Table 3. Also, the value of the proposed power generation for each unit is given in Table 4.

**TABLE 3.** Comparison of the obtained results for the second test system for HHC

Method	Total cost (\$/h)
FAPSO [27]	32659.794
PSO [27]	32858.000
GA [28]	33063.540
DE [28]	32588.865
SPSO [29]	32798.690
SA [30]	32786.400
APSO [31]	32732.770
CSO [30]	32588.918
ACSS [32]	32678.129
<b>HHC</b>	<b>32548.001</b>

**TABLE 4.** The power output for each generator for the second test system for HHC

Unit	Generation (MW)	Unit	Generation (MW)
1	455.001	9	25.0274
2	455.001	10	31.2966
3	129.9784	11	76.6900
4	129.9896	12	79.9885
5	233.8343	13	25.0066
6	460.001	14	15.0080
7	464.9676	15	15.0080
8	60.0481		
<b>Transmission losses (MW)</b>		<b>26.8436</b>	

**4. 3. Third Test System for HHC Algorithm** This test system includes 40 generator units with considering the VPE and the nonlinear fuel cost function. In this ED problem, the purpose is to find the minimum value of the fuel cost like two previous test systems which has been expressed in Equation (1). Data and parameters of this system are given in reference [7]. The power demand of the test system is 10500 MW.

To solve this problem by the HHC algorithm, the accuracy of the survey step is considered to be 0.001 and the speed increase strategies, A and B, are applied simultaneously. Obtained results of the optimal value of the cost function are given in Table 5. Also, the power generation of each generator unit in this system is given in Table 6.

#### 5. IMPLEMENTATION OF THE HHC LOCAL SEARCH ALGORITHM ON THE ECONOMIC DISPATCH PROBLEM WITH COMBINATION OF THE EVOLUTIONARY PSO ALGORITHM IN THE STANDARD TEST SYSTEM (PSOHHC)

To evaluate the efficiency of the PSOHHC algorithm, the same three standard test systems are used which have been mentioned in section 4 of the paper. First, each one of the considered test systems with the PSO algorithm is analyzed and then the obtained results are given to the HHC algorithm to perform the local search around it and improve the results.

##### 5. 1. First Test System for PSOHHC Algorithm

This system has the mentioned characteristics in the fourth section of the paper. In this simulation, the local searcher is allowed to continue the local search operation to reach the closest search space boundary. In the PSO analysis, the initial population was 80 and the number of iterations was 600 and the learning coefficients were 2. Results are given in Tables 7, 8 and the convergence curve is given in Figure 5.

As is clear in Figure 5 and also in section 3.3, the algorithm after finding the best solution compensates the difference value between power demand  $P_D$  and a total of

**TABLE 5.** Comparison of the results in the third test system for HHC

Method	Total cost ( $^{\$/h}$ )
IFEP [20]	123,382.0000
(Poz1) PSO [27]	124,162.4819
FA-PSO [27]	122,471.0751
(Poz2) PSO [27]	125,162.7011
<b>HHC</b>	<b>122,390.0000</b>

**TABLE 6.** The power output for each generator for the third test system for HHC

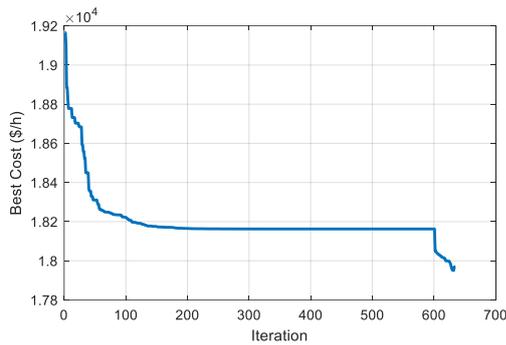
Unit	Generation (MW)	Unit	Generation (MW)	Unit	Generation (MW)
1	113.4374	15	396.9164	28	12.6374
2	113.4374	16	396.9168	29	12.6374
3	100.0374	17	491.9167	30	90.4374
4	182.3704	18	491.9167	31	190.0000
5	90.4374	19	513.9164	32	190.0000
6	140.0000	20	513.9167	33	190.0000
7	262.2374	21	525.9167	34	167.4374
8	287.2374	22	525.9167	35	200.0000
9	287.2374	23	525.9167	36	112.6374
10	132.6374	24	525.9167	37	110.0000
11	96.6374	25	525.9167	38	110.0000
12	96.6374	26	525.9167	39	110.0000
13	217.3971	27	12.6374	40	513.9167
14	113.4374				

**TABLE 7.** Comparison of the obtained results for the first test system for PSOHHC

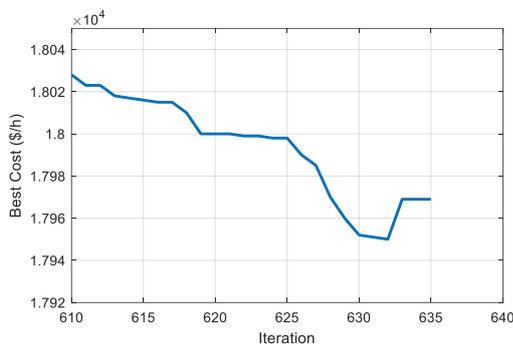
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HS [22]	17,986.5626
GA-PS-PSO [23]	18,199.0000
ST-HDE [24]	18,046.3800
FA [25]	18,029.1600
<b>PSOHHC</b>	<b>17,969.0000</b>

**TABLE 8.** The power output for each generator for the first test system for PSOHHC

Unit	Generation (MW)	Unit	Generation (MW)
1	538.5631	8	109.8722
2	224.6686	9	109.9045
3	149.9527	10	77.46700
4	109.8994	11	40.0037
5	109.8741	12	55.0037
6	109.8768	13	55.0037
7	109.9111		



**Figure 5.** The algorithm's convergence for test system 1 for PSOHHC



**Figure 6.** Details of the fuel cost optimization in test system 1 for PSOHHC

the power generation  $\sum_{i=1}^n P_i$ , which this compensation causes a slight increase in the cost which is determined with more details in Figure 6. This figure shows that the algorithm, after finding the initial PSO results, begins a local search for better solutions around the initial results. This process creates a steep slope (ramp) of the convergence curve. The process of improving the initial results by local search creates this slope in the convergence curve of the proposed algorithm.

**5. 2. Second Test System for PSOHHC Algorithm**

As it has been discussed in section 5.1, the results are given in Tables 9, 10 and the convergence curve is given

**TABLE 9.** Comparison of the obtained results comparison for the second test system for PSOHHC

Method	Total cost (\$/h)
FAPSO [27]	32659.794
PSO [27]	32858.000
GA [28]	33063.540
SPSO [29]	32798.690
SA [30]	32786.400
APSO [31]	32732.770
<b>PSOHHC</b>	<b>32626.001</b>

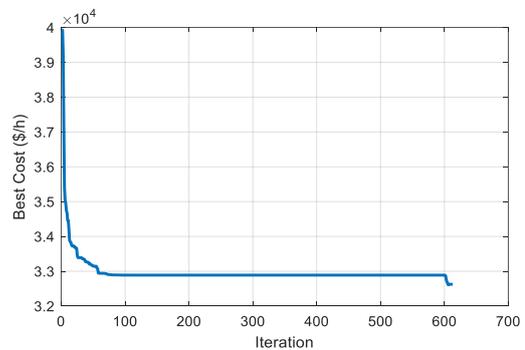
in Figure 7. Also, details of the fuel cost optimization in test system 2 are shown in Figure 8.

**5. 3. Third Test System for PSOHHC Algorithm**

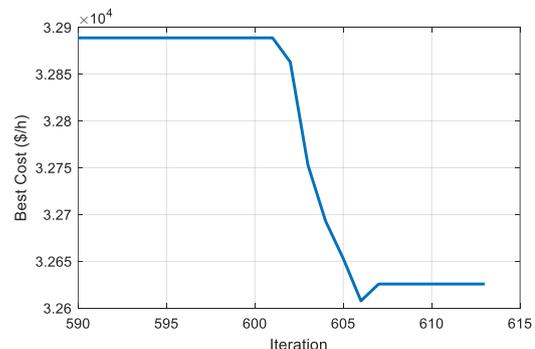
As it has been discussed in section 5.1, the results are presented in Tables 11, 12 and the convergence curve is given in Figure 9. Also, details of the fuel cost optimization in test system 3 are shown in Figure 8.

**TABLE 10.** The power output for each generator for the second test system for PSOHHC

Unit	Generation (MW)	Unit	Generation (MW)
1	399.2373	9	113.1511
2	407.2102	10	100.7767
3	99.7252	11	33.7616
4	129.7175	12	55.0001
5	282.9437	13	24.9999
6	322.9436	14	50.314
7	424.7351	15	35.514
8	149.9700		
<b>Transmission loss (MW)</b>			<b>37.5270</b>



**Figure 7.** The algorithm's convergence for test system 2 for PSOHHC



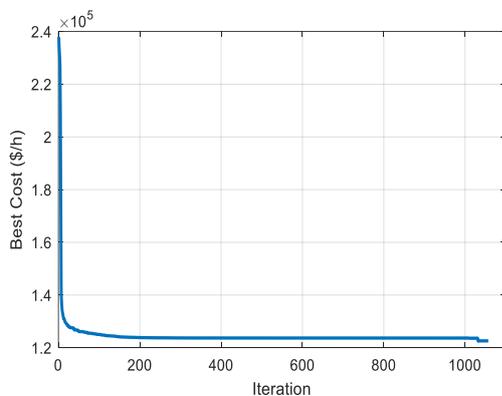
**Figure 8.** Details of the fuel cost optimization in test system 2 for PSOHHC

**TABLE 11.** Comparison of the obtained results comparison for the third test system for PSOHHC

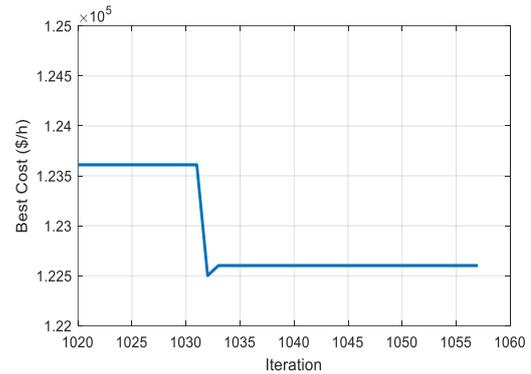
Method	Total cost (\$/h)
IFEP [20]	123,382.0000
(Poz1) PSO [27]	124,162.4819
(Poz2) PSO [27]	125,162.7011
<b>PSOHHC</b>	<b>122,600.000</b>

**TABLE 12.** The power output for each generator for the third test system for PSOHHC

Unit	Generation (MW)	Unit	Generation (MW)	Unit	Generation (MW)
1	74.0864	15	394.3179	28	10.0018
2	110.7965	16	394.2804	29	10.0018
3	97.399	17	489.2878	30	88.0479
4	179.7241	18	489.2811	31	189.9888
5	87.7968	19	511.2816	32	159.7217
6	139.9946	20	511.2810	33	159.7217
7	259.5825	21	523.2827	34	164.7903
8	284.5859	22	433.5228	35	164.7903
9	284.5890	23	523.2820	36	164.7903
10	129.9848	24	523.2818	37	89.1079
11	318.4293	25	523.2813	38	89.1079
12	94.0299	26	523.2807	39	89.1079
13	214.7991	27	10.0018	40	511.2497
14	484.0789				



**Figure 9.** The algorithm's convergence for test system 3 for PSOHHC



**Figure 10.** Details of the fuel cost optimization in test system 3 for PSOHHC

## 6. CONCLUSION

In this paper, a new improved Hybrid Hill Climbing (HHC) algorithm was proposed to solve the economic load dispatch (ED) problem. This algorithm can solve the ED problem through global searching. To make the ED problem conditions more realistic, nonlinear factors and constraints such as the effect of the steam inlet valve (valve point effect (VPE)), the balance between the power generation and power demand in the system, the prohibited operating zones (POZs), ramp rate limits, and transmission line losses were considered. The proposed algorithm with its unique local search capability improves the obtained results in the ED problem. Also, some modification methods were presented to improve the convergence speed of the algorithm and the calculation complexity was analytically evaluated for each case. Other advantages of the proposed method compared to the existing methods are certain results and one-time algorithm implementation. Also, the accuracy of the best solution can be determined by changing the parameter " $\rho$ ", Which in this case, has better efficiency and is more reliable than similar methods mentioned in the references. Evaluating different standard test systems and comparing the results with the existing algorithms approved the capability of the proposed algorithm to find a better solution.

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**Persian Abstract**

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**چکیده**

این مقاله به معرفی الگوریتم جدید تپه‌نوردی ترکیبی (HHC) در حل مساله پخش بار اقتصادی (ED) می‌پردازد. این الگوریتم با یک ساختار جستجوی نظام‌مند با جستجوی سراسری به حل مساله ED می‌پردازد. این الگوریتم قادر است جواب‌های بدست آمده از یک الگوریتم تکاملی دیگر را با جستجوی محلی بهبود داده و به سمت بهترین جواب ممکن متناسب با دقت مورد نیاز مساله، همگرا شود. مهم‌ترین هدف پخش بار اقتصادی، تخصیص بهینه سهم هر ژنراتور جهت تأمین بار و کاهش هزینه‌های واحدهای فعال در سیستم قدرت است. این مساله عموماً با در نظر گرفتن عوامل و محدودیت‌های غیرخطی مانند: اثر شیر ورودی بخار (نقطه دریچه VPE)، توازن تولید و مصرف در سیستم، نواحی عملیاتی ممنوعه (PoZs)، حدود تولید، نرخ شیب و تلفات خطوط می‌باشد. این الگوریتم بر روی ۳ سیستم آزمایش ۱۳ واحدی، ۱۵ واحدی و ۴۰ واحدی با شرایط عملیاتی متفاوت هم به صورت مستقل و همچنین برای همان ۳ سیستم آزمایش به صورت ترکیب شده با الگوریتم تکاملی PSO پیاده‌سازی شده و نتایج شبیه‌سازی نشان‌دهنده کارایی این الگوریتم در حل مسائل ED می‌باشد.

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