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Solving the Economic Load Dispatch Problem Considering Units with Different Fuels Using Evolutionary Algorithms

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Abstract

Nowadays, economic load dispatch between generation units with least cost involved is one of the most important issues in utilizing power systems. In this paper, a new method i.e. Water Cycle Algorithm (WCA) which is similar to other intelligent algorithm and is based on swarm, is employed in order to solve the economic load dispatch problem between power plants. In order to investigate the effectiveness of the proposed method in solving non-linear cost functions which is composed of the constraint for input steam valve and units with different fuels, a system with 10 units is studied for more accordance with literatures in two modes: one without considering the effect of steam valve and load of 2400, 2500, 2600 and 2700 MW and the other one with considering the effect of steam valve and load of 2700 MW. The results of the paper comparing to the results of the other valid papers show that the proposed algorithm can be used to solve in any kind of economic dispatch problems with proper results.

Keywords: Economic load dispatch, water cycle algorithm, valve- point effect.

1. Introduction

Most of the optimization problems in power systems such as economic load dispatch have complicated and non-linear features with equality and inequality constraints. This causes it hard to be mathematically solved [1]. Economic load dispatch is an important issue in the field of management and utilization of power system where the aim is to determine the production value of each power plant in a way the load of system is supplied with least cost while all the constraints are fulfilled.

Obtaining the optimal solution is sometimes difficult in solving the economic load dispatch problem due to complication of fuel cost function of power plants and also due to some limitation. One of these complications is related to the actual form of cost function. It has to be noted that in practice cost function of a power plant has no smooth form. In other words, this cost function has local maximum and minimum and usually it is not derivable in these points [2-3].

Different optimization methods and techniques have been used to solve the problem of economic load dispatch. Some of these methods are based on mathematical methods such as linear and quadratic programming [4-5]. Linear programming methods are generally quick and use linear and step approximation of fuel cost which in turn reduces the accuracy of the problem. To overcome this problem, non-linear programming methods is used. However, non-linear programming method has difficulties in convergence and also with an increase in the number of units the required time and memory to solve the problem would considerably increase.

To overcome such problems evolutionary algorithms are proposed. These algorithms have several distinct advantages such as using probable search instead of explicit methods and also effectively finding the general optimal points instead of local optimal points. For instance, Artificial Neural Network [6], Genetic Algorithm [7], Simulated Annealing [8], Ant Colony Optimization [9] are some of these algorithms. In ref [10], a new algorithm named Artificial Life is proposed to minimize a non-convex combinatorial function. Interactive Honey Bee Mating Optimization [11] and Artificial Immune Systems [12-13] are used to solve economic load dispatch problem.

In this paper, a novel evolutionary algorithm which is based on the water cycle algorithm and is inspired from water cycle in the nature is proposed to solve the economic load dispatch (ELD) between power plants considering actual model of non-smooth cost functions on a test system with 10 units with and without the effect of steam valve. The rest of the paper is organized as follow. Problem description is presented in section 2. In section 3, a comprehensive definition of the water cycle algorithm (WCA) is expressed and the application of WCA in solving the ELD is presented in section 4. Simulation and conclusion are presented in section 5 and 6, respectively.

2. Economic Load Dispatch Problem

As mentioned before, ELD is defined as a process of allocating the levels of generation for each power plant in combinatorial form in a way the demand of system is supplied completely and economically [14].

In order to reach to optimal production for each power plant, curve of fuel cost has to be modeled as a mathematical relation. In classic case, this function is modeled as quadratic function (Figure 1) but in practical and developed cases; this model is modeled as non-linear and discontinues form due to several constraints.

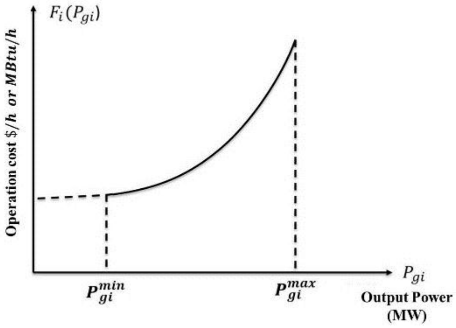

Fig.1. The curve of fuel cost for generators in smooth and continues condition

The first relation in optimal load dispatch problem is the law of conservation of energy. The sum of generated power by power plants has to be equal to the load demanded from grid.

$$\sum_{i=1}^{ng} P_{gi} = P_D \tag{27}$$

Where P_D is the demand power, P_{gi} power generated (output power) by i_{th} generator, ng number of generators in the system.

In more complex load dispatch problems, the loss of transmission network (P_L) has to be added to the equation (1).

$$\sum_{i=1}^{ng} P_{gi} = P_D + P_L \tag{28}$$

Equation (2) expresses that the sum of generated power is equal to sum of the consuming power including power consumed in loads and power wasted in transmission line. This equation is a form of the law of conservation of energy. The value of P_L is calculated by equation (3).

$$P_L = \sum_{i=1}^{ng}\sum_{j=1}^{ng} P_{gi} B_{ij} P_{gj} + \sum_{i=1}^{ng} B_{0i} P_{gi} + B_{00} \tag{29}$$

Where B_{ij}, B_{0i} and B_{00} are factors of loss function for transmission network. Fuel cost of each power plant is calculated from the following relation.

$$F(P_{gi}) = a_i P_{gi}^2 + b_i P_{gi} + c_i \tag{30}$$

Where F is fuel cost and c_i, b_i, a_i are factors for fuel cost function of i_{th} unit.

In Figure 1, P_{gi}^{min} is the minimum loading range that below this range it would not be economical (or technically impossible) for the unit and P_{gi}^{max} is output maximum range for unit. Therefore, output power of generator has to be within minimum and maximum ranges.

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \tag{31}$$

In steam plants, several steam valves are used in turbine for controlling the output power of the generators. Opening the steam valve would lead to a sudden increase in loss and causes ripples in input-output curve and consequently causes cost function non-smooth. If the effect of steam valve is considered in power plants, cost function of their generation would take a non-smooth form due to related mechanical effects.

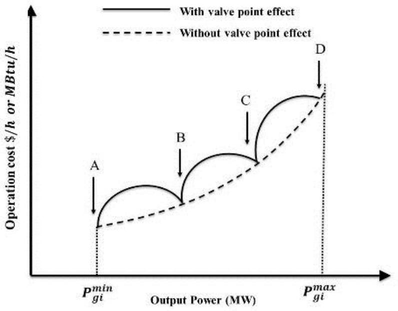

Fig.2. Fuel cost curve for generators with 4 steam valves

This influence is usually modeled by adding a sinusoidal term in cost function of power plants. Therefore, equation (4) considering the effect of input steam valve is expressed as equation (6) [15].

$$F_i(P_{gi}) = a_i P_{gi}^2 + b_i P_{gi} + c_i + \left|e_{gi} \times Sin\left(f_{gi} \times (P_{gi}^{min} - P_{gi})\right)\right| \quad (32)$$

Where e_{gi} and f_{gi} are factors for the effect of valve point on i_{th} generator.

When generation units perform with different kinds of fuels, cost function of each unit is expressed by some quadratic equations where each one of them corresponds to one kind of fuel. This is formulated mathematically as in equation (7) [16-17].

$$F_i(P_{gi}) = \begin{cases} a_{i1}P_{gi}^2 + b_{i1}P_{gi} + c_{i1} \ , P_{gi}^{min} \le P_{gi} \le P_{gi1} & , fuel1 \\ a_{i2}P_{gi}^2 + b_{i2}P_{gi} + c_{i2} \ , P_{gi1} \le P_{gi} \le P_{gi2} & , fuel2 \\ \vdots & \\ \vdots & \\ a_{ik}P_{gi}^2 + b_{ik}P_{gi} + c_{ik} \ , P_{gi,k-1} \le P_{gi} \le P_{gi}^{max} & , fuel\ k \end{cases} \quad (33)$$

a_i, b_i, c_i express the factors for fuel cost function of i_{th} unit.

3. Water Cycle Algorithm

In this section, a new algorithm inspired by water cycle in nature is presented which is not employed for optimization on any power systems [18]. Similar to other heuristic swarm algorithms, the proposed method is started with an initial population named rain drops (N_{pop}). A matrix is produced as rain drops with a dimension of N_{pop}*N_{var} for initializing the optimization. Rows and columns of this matrix are composed of population (N_{pop}) and number of design variables (N_{var}) or generation units, respectively.

$$\text{Population of raindrops} = \begin{bmatrix} Raindrop_1 \\ Raindrop_2 \\ Raindrop_3 \\ \vdots \\ Raindrop_{N_{pop}} \end{bmatrix} = \begin{bmatrix} X_1^1 & X_2^1 & X_3^1 & \dots & X_{N_{var}}^1 \\ X_1^2 & X_2^2 & X_3^2 & \dots & X_{N_{var}}^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ X_1^{N_{pop}} & X_2^{N_{pop}} & X_3^{N_{pop}} & \dots & X_{N_{var}}^{N_{pop}} \end{bmatrix} \quad (34)$$

In a random matrix with certain dimension, the values of every variable $X_1, X_2, X_3, \dots, X_N$ can be real or complex. Cost function or cost of the problem is defined as below:

$$Cost_i = f\left(X_1^i, X_2^i, \dots, X_{N_{var}}^i\right), i = 1,2,3,\dots,N_{pop} \quad (35)$$

After producing the initial matrix, N_{SR} number of them is considered as sea and rivers. Besides, a drop with the best answer is chosen as sea. The other members as rain drops would flow to the rivers or directly to the sea. In fact, N_{SR} is the sum of river (user parameter) and sea.

$$N_{SR} = Number\ of\ Rivers + \underbrace{1}_{Sea} \quad (36)$$

It would be understood which drop will go to which river based on the stream intensity of each river:

$$NS_N = round\left\{\left|\frac{Cost_n}{\sum_{i=1}^{N_{sr}} Cost_i}\right| \times N_{Raindrops}\right\} \quad (37)$$

$n = 1,2,\dots,N_{SR}$

After flowing the drop to the river, it has to be known that how rivers are flown down to seas. Movement of each stream to a river is known by a line that joins them. This distance is calculated randomly.

$$X \in (o, C \times d) \ , \ C > 1 \quad (38)$$

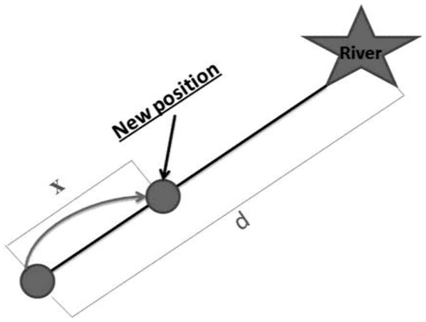

Fig.3. Schematic of flowing a stream to a river

Where C is a value between 1 and 2 (near to 2). The current distance between stream and river is shown by parameter d. X in equation (14) is a random value between 0 and C*d. The values of C greater than 1 enables stream to flow to the river in different directions. Therefore, the best value for C would be 2. This concept can be used in flowing rivers to the sea. Hence, new positions for stream and river can be defined as follow [19].

$$X_{Stream}^{i+1} = X_{Stream}^i + rand \times C \times \left(X_{River}^i - X_{Stream}^i\right) \quad (39)$$

$$X_{River}^{i+1} = X_{River}^i + rand \times C \times \left(X_{Sea}^i - X_{River}^i\right) \quad (40)$$

Where rand is a random number with uniform distribution between 0 and 1. After updating the position of each drop and investigating the objective function, if the proposed solution by stream is better than a river connected to it, position of stream and river are changed (i.e. stream would be river and vice versa). This displacement could be happened for river and sea.

The evaporation criterion is investigated after the abovementioned stages. When the position of a stream or river is completely corresponding with the position of a sea, it means that it has flown to sea. In this condition, evaporation is done and new streams and drops are again flown to the mountains by rain and the above procedure is repeated.

$$if\left|X_{Sea}^{i}-X_{River}^{i}\right|<d_{max}\ ,i=1,2,3,\dots,N_{sr}-1 \quad (41)$$

Where d_{max} is a small number near to zero and controls the depths of search close to sea. Greater values of d_{max} increase the search space and small values if depth. d_{max} is decreased in any repetition.

$$d_{max}^{i+1}=d_{max}^{i}-\frac{d_{max}^{i}}{max\ iteration} \quad (42)$$

If the above condition is set, rain will come and all the above procedure would be repeated. Equation (19) is used for specifying the new position of newly produced streams.

$$X_{Stream}^{new}=LB+rand\times(UB-LB) \quad (43)$$

Where LB and UB are the lower and upper range of the problem, respectively. Besides, there may some streams that would flow directly to the sea without flowing to a river.

$$X_{Stream}^{new}=X_{Sea}+\sqrt{\mu}\times randn(1,N_{var}) \quad (44)$$

Where μ is the search domain near to sea. randn is a random number of normal distribution. Great values for μ increase the possibility of going out of the possible area. Besides, small values for μ causes the algorithm to search in a smaller area near to sea. The best value for μ is selected 0.1.

Stop criterion in heuristic algorithm is usually the best calculated answer in which stop criterion would be defined as maximum number of iteration, processing time or ε a non-negative small value as tolerance between two previous results. Performance of WCA is agreeable to maximum iteration as a convergence criterion.

4. Application of WCA on ELD problem

In this paper, a new algorithm called Water Cycle is used to optimize the overall fuel cost of power plants. At first, the initial values of WCA like Npop, Nsr and data related to generation units such as factors of fuel cost function of generators, output limitations of generators and the demanded load are summoned by the system. After this, population matrix of drops is produced in a random manner. At third stage, constraints of the ELD problem are investigated.

In order to investigate the power balance condition, the value of $\emptyset$ is calculated for each population like according to the following equation:

$$\emptyset=(P_D+P_L)-\sum_{i=1}^{ng}P_{gi} \quad (45)$$

If $\emptyset$=0, it means that the inequality constraint is met; otherwise, the calculated $\emptyset$ is added to a unit randomly. Inequality constraint is then checked for that unit. If the power is more than maximum power of that unit, power is set to the maximum value. Since $\emptyset$ can also be negative, so if the power is less than the minimum power of that unit, then the power is set to minimum value. Therefore, we have:

$$P_{gi}=\begin{cases}P_{gi}^{max} & if\quad P_{gi}>P_{gi}^{max}\\ P_{gi}^{min} & if\quad P_{gi}<P_{gi}^{min}\end{cases} \quad (46)$$

Now we go back to the second stage and repeat it until $\emptyset=0$.

For solving the ELD problem when there are different kinds of fuels, the considered production range for each unit is divided to some sub range (usually 3 sub ranges) and if the production power is put in a sub range, the fuel kind of that range is introduced as the optimum fuel for that unit. In fact, this constraint makes a piecewise quadratic cost function and consequently difficult optimization. There are a few studies in this field considering the simultaneous effect of input steam valve.

At fourth stage, cost of one drop and at fifth stage the intensity of stream for river and sea re calculated. At sixth stage, flowing the streams to the rivers and rivers to the seas are investigated. After updating the position of each drop and investigating the objective function, if the proposed solution by a stream is better than a river connected to it, position of stream and river are changed (seventh stage). This stage could be happened for river and sea (eighth stage). Evaporation condition which has an important role in preventing the algorithm to be trapped in the local minima is investigated. At next stage, d_{max} is reduced. When the distance between river and sea is less than d_{max}, it means that river has reached to the sea. In other words, if the evaporation condition is met, rain will occur based on equations (19) and (20). And finally stop criterion is checked. Performance of WCA is usually agreeable to maximum iteration as a convergence criterion. If the stop criterion is met, algorithm will stop; otherwise it goes back to the third stage.

5. Simulation

In this kind of problem some different consuming fuels are considered for different production ranges of generators which make a quadratic cost function.

5.1. System with 10 units without considering the effect of steam valve

To investigate this kind of ELD problem, a system with 10 units with loads of 2400, 2500, 2600 and 2700 MW without considering the effect of input steam valve is taken into account as the first test system. Parameters of the algorithm in this test is set as follow

$$N_{pop} = 100\,, N_{sr} = 30\,, d_{max} = 0{,}1 \quad , C = 2 \quad , U = 0.1$$

Figure 4 and Tables 1 and 2 show the convergence diagram, optimum solutions and comparison with other methods, respectively.

Table.1
Results of WCA for system with 10 units considering the effect of input steam valve

Unit No	2400(MW)		2500(MW)		2600(MW)		2700(MW)	
	Output	F	Output	F	Output	F	Output	F
1	189.73	1	206.52	2	216.58	2	218.27	2
2	202.35	1	206.45	1	210.88	1	211.67	1
3	253.89	1	265.74	1	278.51	1	280.72	1
4	233.05	3	235.95	3	239.07	3	239.63	3
5	241.85	1	258.01	1	275.53	1	278.49	1
6	233.04	3	235.95	3	239.18	3	239.63	3
7	253.26	1	268.87	1	285.70	1	288.60	1
8	233.04	3	235.95	3	239.13	3	239.63	3
9	320.38	1	331.49	1	343.52	3	428.47	3
10	239.40	1	255.05	1	271.97	1	274.87	1
$F_{total\ (S/h)}$	481.7216		526.2279		574.3791		623.798	

Table.2
Comparison of WCA results by different methods without considering the effect of input steam valve

Method	Fuel cost $/h			
	2400(MW)	2500(MW)	2600(MW)	2700(MW)
HNUM[20]	488.50	526.70	574.03	625.18
HNN[21]	487.87	526.13	574.26	626.12
AHNN[22]	481.72	526.23	574.37	626.24
ELANN[23]	481.74	526.27	574.41	623.88
IEP[24]	481.779	526.304	574.473	623.851
DE[25]	481.723	526.239	574.381	623.809
MPSO[26]	481.723	526.239	574.381	623.809
RCGA[27]	481.723	526.239	574.396	623.809
AIS[28]	481.723	526.240	574.381	623.809
HICDEDP[29]	481.723	526.239	574.381	623.809
EALHN[30]	481.723	526.239	574.381	623.809
WCA	481.7216	526.2279	574.3791	623.7980

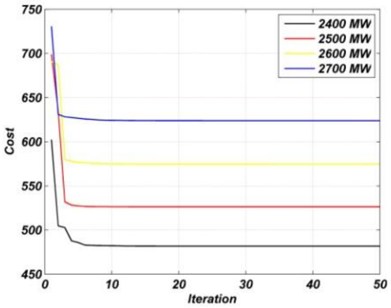

Fig.4. Convergence diagram of WCA for system with 10 units and loads of 2400 to 2700 MW

As illustrated in the results of system with 10 units without considering the effect of steam valve, this system has the best cost in loads of 2400 to 2700 MW in comparison to the other methods. Besides, Figure 4 shows that this system without considering the effect of steam valve with load of 2400 MW converges quicker than the same system with load of 2700 MW.

5.2. System with 10 units considering the effect of input steam valve

There are no too many researches to combine the effect of input steam valve and the constraint of different consuming fuels in the ELD problem. For this purpose, the second test system is considered with adding the effect of steam valve to previous system and load of 2700 MW. Parameters of algorithm for this system are similar to the previous system. Figure 5 and Table 3 present convergence diagram and comparison of the results with other methods, respectively.

Table.3
Comparison of WCA results for system with 10 units considering the effect of input steam valve and load of 2700 MW

	CGA_MU[31]		IGA_MU[31]		WCA	
Unit No	Output	F	Output	F	Output	F
1(MW)	222.0108	2	219.1261	2	220.0550	2
2(MW)	211.6352	1	211.1645	1	210.9169	1
3(MW)	283.9455	1	280.6572	1	279.6702	1
4(MW)	237.8052	3	238.4770	3	238.7458	3
5(MW)	280.4480	1	276.4179	1	280.1485	1
6(MW)	236.0330	3	240.4672	3	239.6610	3
7(MW)	292.0499	1	287.7399	1	287.7073	1
8(MW)	241.9708	3	240.7614	3	239.6864	3
9(MW)	424.2011	3	429.3370	3	427.4088	3
10(MW)	269.9005	1	275.8518	1	275.9998	1
$F_{total\ (S/h)}$	624.7193		624.5178		623.8509	

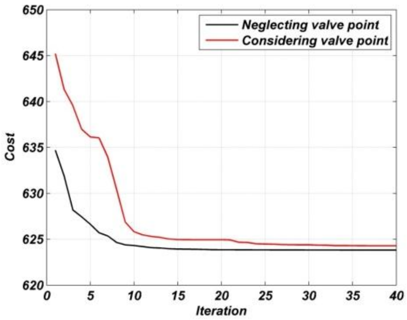

Fig.5. Convergence diagram of WCA for system with 10 units considering the effect of input steam valve and load of 2700 MW

There are a few researches to simultaneously study the effect of steam valve and units with different fuels in system with 10 units with considering the effect of steam valve due to complications. Therefore, there was just a system surveyed once with load of 2700 MW. Fuel cost of this system is 623.8509 which are improved slightly comparing to the other two algorithms. Figure 5 illustrates a comparison of system with 10 units and load of 2700 MW with and without the effect of steam valve. The effect of steam valve makes convergence a little difficult and increases the probability of converging to the local minimums. In the first mode, convergence was achieved at about 10 iterations but the effect of steam valve delayed it to 25 iterations.

5.3. Sensitivity analysis of algorithm C

As mentioned before, this parameter controls the way of flowing from streams to rivers and seas and has a value between 0 and 2. Values higher than 1 causes the streams to be able to flow in two directions. Table 4 and Figure 6 present the comparison of results for 4 different values of this test system.

Table.4
Results of WCA for system with 10 units and load of 2700 MW and different values of C

	C =0.1		C =0.8		C=1.4		C =2	
Unit No	Output	F	Output	F	Output	F	Output	F
1(MW)	219.5905	2	215.2694	2	212.0377	2	220.0550	2
2(MW)	207.1839	1	222.9899	1	215.1524	1	210.9169	1
3(MW)	297.7758	1	283.4461	1	279.4089	1	279.6702	1
4(MW)	242.3708	3	241.0252	3	240.6257	3	238.7458	3
5(MW)	311.3986	1	294.1461	1	279.5790	1	280.1485	1
6(MW)	245.5736	3	244.8194	3	240.0692	3	239.6610	3
7(MW)	302.0291	1	277.4023	1	285.1218	1	287.7073	1
8(MW)	244.5238	3	243.4481	3	236.9990	3	239.6864	3
9(MW)	350.3311	3	393.6467	3	424.3429	3	427.4088	3
10(MW)	279.1511	1	283.6891	1	286.5712	1	275.9998	1
$F_{total\ (S/h)}$	627.4213		626.3751		624.3440		**623.8509**	

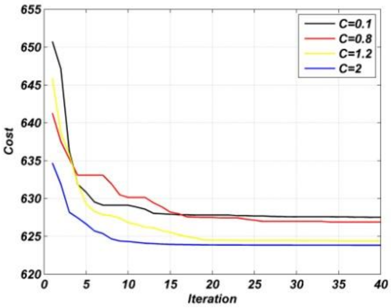

Fig.6. Sensitivity analysis diagram of WCA for system with 10 units and load of 2700 MW and parameter C

5.4. Sensitivity analysis of Parameter d_{max}

As mentioned in this section, this parameter prevents algorithm from quick convergence and to be trapped in local minima. The value of this parameter is updated after each iteration. Results and convergence diagram for three different values of d_{max} are shown in Figure 7 and Table 5, respectively.

6. Conclusion

In this paper, a new algorithm is employed in order to solve the economic load dispatch problem. This algorithm uses fewer factors to reach to the optimum solution comparing to the other algorithms which causes this algorithm to solve the problems quicker while maintaining the accuracy. In order to show the ability of WCA in solving non-linear problems, a system with 10 units in two modes is investigated i.e. with and without considering the effect of steam valve.

Table.5
Results of WCA for system with 10 units and load of 2700 MW and different values of d_{max}

	d_{max} =2		d_{max} =0.1		d_{max} =0.01	
Unit No	Output	F	Output	F	Output	F
1(MW)	218.5807	2	220.0550	2	216.3999	2
2(MW)	214.1351	1	210.9169	1	211.4120	1
3(MW)	280.6462	1	279.6702	1	284.4471	1
4(MW)	239.2832	3	238.7458	3	240.7613	3
5(MW)	273.7120	1	280.1485	1	278.8212	1
6(MW)	239.1236	3	239.6610	3	237.2423	3
7(MW)	287.7891	1	287.7073	1	289.7176	1
8(MW)	239.9551	3	239.6864	3	240.8957	3
9(MW)	427.5427	3	427.4088	3	425.7371	3
10(MW)	279.1428	1	275.9998	1	274.5656	1
$F_{total\ (S/h)}$	623.9863		**623.8509**		623.9657	

In this system when the effect of steam valve is not considered, as observed from the related Table, the cost of this system is obtained as 481.7216, 526.2279, 574.3791 and 623.7980 for loads of 2400 to 2700 MW. These results are less than all the other methods and more near to optimum value. Although this reduction is not very noticeable, it is very valuable considering the type of problem and other performed researches up to now in ELD problem with different kinds of fuels. In this system when the effect of steam valve is considered, this effect makes convergence a little difficult and increases the probability of converging to the local minimums. In the first mode, convergence was achieved at about 10 iterations but the effect of steam valve delayed it to 25 iterations. At last, Sensitivity analysis of Parameters C and dmax was carried out on a system with 10 units and load of 2700 MW. As shown by the results and section 3, the best value for parameter C is 2 which give the best results. The results of parameter dmax shows that higher values of this algorithm increase discovery range and search span of the algorithm but too high values of this parameter worsens the quality of the solution. Besides, too low values of this parameter would also lead to solution with little quality but a proper reduction in this parameter increases the convergence.

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