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Optimization the Combined Heat and Power Economic Dispatch problem using Harmony Search Algorithm

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Abstract: Recently, combined heat and power units, known as cogeneration, which produce both heat and electrical power, have played an increasing in different industries. In order to utilize CHP units more efficiently, economic dispatch problem is applied to determine the optimal combination of the power and heat outputs of system while satisfying heat and power demand and other constraints with minimum fuel cost. This problem is known as combined heat and power economic dispatch (CHPED). Due to complex characteristics, heuristic and evolutionary based optimization approaches have became effective tools to solve the CHPED problem. The problem which is used in this paper is non-linear, non-smooth and non-convex. Harmony Search Algorithm is applied to two tests with different characteristics. The obtained results demonstrate the efficiency of the proposed method in solving non-convex and non smooth problems, with considering and non considering the transmission loss and also with both equal and different initialization of the problem for the same CHP units.

Keywords: Combined heat and power (CHP), Cogeneration, economic dispatch (ED), Harmony Search algorithm (HS), Optimization

Introduction

The energy efficiency of the most efficient conventional power production unit is less than 60%, but the fuel efficiency of combined heat and power (CHP) production unit can be as much as 90% [1,3]. Beside its high efficiency, CHP results in the reduction of environmental pollutants (CO2, SO2, SOx, and, NOx emissions) by about 13–18% [2]. In order to utilize CHP units more efficiently, economic dispatch problem is applied to determine the optimal combination of the power and heat sources' outputs to satisfy heat and power demand of system and operational constraints. This problem is known as CHP economic dispatch (CHPED) problem and has attracted a lot of interests in recent years. Dual dependency of heat and power production in CHP units makes the CHPED problem a complicated optimization problem, which needs powerful optimization techniques to solve it. The CHPED problem will be more complex if the effects of the valve-point in cost function and system losses are taken into account. Considering valve-point effects make the CHPED problem non-convex. Hence, using gradient based classic optimization methods does not guarantee obtaining the optimal solution. Because non-convex CHPED problem has a lot of local optima and in most cases, classical methods find a relative optimum (or local optimum) that is closest to the starting point.

Stochastic search methods which are not based on the gradient of the objective function are used to solve constrained CHPED problem. These methods can give a good solution with reasonable computation time where the exact methods fail to produce a solution or they are too slow.

In this paper, the CHPED problem is solved using stochastic search method appeled Harmony Search algorithm (HS). This algorithm was inspired by the music improvisation process in which the musician searches for harmony and continues to polish the pitches to obtain a better harmony. The first time, Harmony Search algorithm was introduced by Geem et al in [4]. Here, the Harmony Search algorithm is applied to solve non-linear, non-convex and non-smooth CHPED problem with considering valve-point effects and system losses on a test system which consists of 7 units and also without considering the system losses on a test system consisting of 5 units with both equal and disparate initialization of the problem for same combined heat and power units.

Formulation of CHPED problem

The CHPED problem is to determine the power and heat of a unit production so that the system production cost is minimized while the power and heat demands and other constraints are satisfied. Mathematically; the problem is to minimize the following objective function [5].

$$Minimize\ F_{fuel} = \sum_{i=1}^{N_p} f_i(P_i) + \sum_{j=1}^{N_c} f_j\left(P_j, h_j\right) + \sum_{k=1}^{N_h} f_k(h_k) \qquad (1)$$

Where N_p, N_c and N_h are the number of conventional thermal units, cogeneration units and heat-only units, respectively; h and P are the heat and electrical power output of unit, respectively. $f_i(P_i)$, $f_j\left(P_j, h_j\right)$ and $f_k(h_k)$ represent the fuel cost function of i-th power-only unit, fuel cost function of j-th cogeneration unit and fuel cost function of k-th heat-only unit, respectively[5].

Quadratic fuel cost function of power-only units may be written as:

$$f_i(P_i) = a_i\left({P_i}^2\right) + b_i(P_i) + c_i \ \Big|\ \$ \qquad (2)$$

Where, a_i, b_i and c_i are the cost coefficients of the i-th power-only unit. In a practical generation unit, steam valve admission effects lead to the ripple in the production cost. In order to model this effect more accurately, a sinusoidal term is added to the quadratic cost function. Considering valve-point effects make the problem non-convex and non-differentiable. The unit cost function considering valve-point effects is represented as follows.

$$f_i(P_i) = a_i\left({P_i}^2\right) + b_i(P_i) + c_i + \left|d_i \sin\left(e_i(P_i^{min} - P_i\right)\right|\$ \qquad (3)$$

Where, d_i and e_i are the cost coefficients for modeling the valve-point effects.

The production cost of cogeneration and heat-only units are defined as:

$$f_j\left(P_j, h_j\right) = a_j\left({P_j}^2\right) + b_j\left(P_j\right) + c_j + d_j\left(h_j^2\right) + e_j\left(h_j\right) + f_j\left(P_j\ h_j\right)\Big|\$ \qquad (4)$$

$$f_k(h_k) = a_k\left({h_k}^2\right) + b_k(P_k) + c_k \ \Big|\$ \qquad (5)$$

Where,a_j,b_j,c_j ,d_j , e_j and f_j are the cost coefficients of the j-th cogeneration unit; a_k, b_k and c_k represent the cost coefficient of k-th heat-only unit.

The objectives function of the CHPED problem, which is to be minimized, Subject to the equality and inequality constraints.

Equality Constraints

Heat and power balance constraints

$$\sum_{i=1}^{N_p} P_i + \sum_{j=1}^{N_c} P_j = P_D + P_L\Big|\ MW \qquad (6)$$

$$\sum_{j=1}^{N_c} h_j + \sum_{k=1}^{N_h} P_k = H_D\Big|\ \text{MWth} \qquad (7)$$

Where, P_D and H_D are total power and heat demands of system, respectively. P_L is the total active power transmission loss. Transmission losses of the system should be taken into account in order to meet the load demand exactly.

The B-coefficient method is one of the most commonly used by power utility industry to calculate the network losses. In this method the total active power transmission loss is expressed as a quadratic function of the unit power outputs that can be approximated in the following [6]:

$$P_L = \sum_{i=1}^{N_p+N_C} \sum_{j=1}^{N_p+N_C} P_i B_{ij} P_j \Big| MW \quad (8)$$

Where, B_{ij} the loss coefficient for a network branch connected between buses *i* and *j*.

Inequality Constraints

Capacity limit constraints

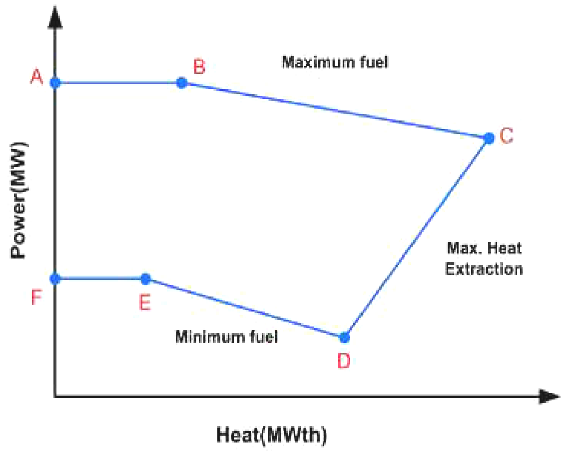
$$P_i^{min} \le P_i \le P_i^{Max} \qquad i = 1, \dots, N_p \quad (9)$$

$$P_j^{min}(h_j) \le P_j \le P_j^{Max}(h_j) \qquad j = 1, \dots, N_C \quad (10)$$

$$h_j^{min}(P_j) \le h_j \le h_j^{Max}(P_j) \qquad j = 1, \dots, N_C \quad (11)$$

$$h_k^{min} \le h_k \le h_k^{Max} \qquad k = 1, \dots, N_h \quad (12)$$

Where, P_i^{min} and P_i^{Max} are the minimum and maximum power outputs of i-th conventional unit in MW; $P_j^{min}(h_j)$, $P_j^{Max}(h_j)$, $h_j^{min}(P_j)$ and $h_j^{Max}(P_j)$, are the linear inequalities that define the feasible operating region of the j-th CHP unit; h_k^{min} and h_k^{Max} are also the minimum and maximum thermal outputs of the k-th heat-only unit. It is obvious that the heat production limits of CHP units are dependent to the unit power production and vice versa. The heat-power Feasible Operation Region (FOR) for a CHP unit is depicted in (Figure 1) [6]. The upper and lower bounds of heat and power units are restricted by their own generation limits [7].



Figur unit.

Harmony Search Algorithm

Harmony Search. Firstly developed by Geem et al. in 2001, harmony search (HS) [4] is a relatively new meta-heuristic optimization algorithm, and it is based on natural musical performance processes that occur when a musician searches for an optimal state of harmony. The optimization operators of HS algorithm are specified as the harmony memory (HM), which keeps the solution vectors which are all within the search space; the harmony memory size HMS, which represents the number of solution vectors kept in the HM; the harmony memory consideration rate (HMCR); the pitch adjustment rate (*PAR*); the pitch adjustment bandwidth (*bw*).
In the HS algorithm, musical performances seek a perfect state of harmony determined by aesthetic estimation, as the optimization algorithms seek a best state (i.e. global optimum) determined by objective function value. It has been successfully applied to various optimization problems in computation and engineering fields [8].
The optimization procedure of the HS algorithm consists of steps 1–5, as follows:
Step 1: Initialize the optimization problem and algorithm parameters.
Step 2: Initialize the harmony memory HM.
Step 3: Improvise a new harmony from the HM.
Step 4: Update the HM.
Step 5: Repeat Steps 3 and 4 until the termination criterion has been satisfied.
The detailed explanation of these steps can be found in [4] which are summarized in the following:

Step 1. Initialize the optimization problem and HS algorithm parameters.

First, the optimization problem is specified as follow:

$$Minimize\ f(x)\ \ subject\ to\ x_i \in X_i, \qquad i = 1, \dots, N$$

Where *f(x)* is the objective function, *x* is the set of each decision variable (x_i); X_i is the set of the possible range of values for each design variable (continuous design variables), that is, $x_{i\ lower} \leq X_i \leq x_{i\ upper}$, where $x_{i\ lower}$ and $x_{i\ upper}$ are the lower and upper bounds for each decision variable; and (*N)* is the number of design variables. In this context, the HS algorithm parameters that are required to solve the optimization problem are also specified in this step. The number of solution vectors in harmony memory (HMS) that is the size of the harmony memory matrix, harmony memory considering rate (HMCR), pitch adjusting rate (*PAR*), and the maximum number of searches (stopping criterion) are selected in this step. Here, HMCR and *PAR* are parameters that are used to improve the solution vector. In this context, both are defined in Step 3.
Step2. Initialize the harmony memory (HM).

The harmony memory (HM) is a memory location where all the solution vectors (sets of decision variables) are stored. In Step 2, the HM matrix, shown in (Eq.13), is filled with randomly generated solution vectors using a uniform distribution,

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \qquad (13)$$

Step3. Improvise a new harmony from the HM.

A new harmony vector $x' = (x'_1, \dots, x'_N)$ is generated based on three rules: (a) memory consideration, (b) pitch adjustment, and (c) random selection. Generating a new harmony is called 'improvisation'. In the memory consideration, the value of the first decision variable (x'_1) for the new vector is chosen from any value in the specified HM range ($x'_1, \dots, x_N^{HMS}$). Values of the other decision variables ($x'_2, \dots, x_N^{HMS}$) are chosen in the same manner.
The HMCR, which varies between 0 and 1, is the rate of choosing one value from the historical values stored in the HM, while (1-HMCR) is the rate of randomly selecting one value from the possible range of values.

$$x'_i \leftarrow \begin{cases} x'_i \in \{x_i^1, x_i^2, \cdots, x_i^{MHS}\}\ w.p.(HMCR) \\ x'_i\ \in\ X_i\ \cdots\cdots\cdots\ w.p.(1 - HMCR) \end{cases} \qquad (14)$$

After, every component obtained by the memory consideration is examined to determine whether it should be pitch-adjusted. This operation uses the PAR parameter, which is the rate of pitch adjustment as follows:

$$Pitch\ adjuseting\ decision\ for\ \ x'_i \leftarrow \begin{cases} Yes \quad with\ probability \quad PAR \\ No \quad with\ probability \quad (1 - PAR) \end{cases} \qquad (15)$$

The value of (*1 -PAR*) sets the rate of doing nothing. If the pitch adjustment decision for x'_i is yes, then x'_i is replaced as follows:

$$x'_i \leftarrow x'_i \pm\ r.bw \qquad (16)$$

Where *bw* is an arbitrary distance bandwidth, *r* is a random number generated using uniform distribution between 0 and 1. In Step 3, HM consideration, pitch adjustment or random selection is applied to each variable of the New Harmony vector in turn.
Step4. Update the HM.
If the new harmony vector,($x'_1, \dots, x'_N$) is better than the worst harmony in the HM, judged in terms of the objective function value, the new harmony is included in the HM and the existing worst harmony is excluded from the HM.
Step5. Repeat Steps 3 and 4 until the termination criterion has been satisfied.
The *HMCR* and *PAR* parameters introduced in Step 3 help the algorithm find globally and locally improved solutions, respectively [8].

PAR and *bw* in HS algorithm are very important parameters in fine-tuning of optimized solution vectors, and can be potentially useful in adjusting convergence rate of algorithm to optimal solution. So fine adjustment of these parameters are of great interest.

Mahdavi and al. [9] proposed an improved harmony search algorithm that uses variable *PAR* and *bw* in improvisation step. The HS proposed in this work has exactly the same steps of classical HS with exception that Step 3, where the HS proposed dynamically updates *PAR* in which concepts from dispersed particle swarm optimization are adopted. The key difference between HS proposed and traditional HS method is in the way of adjusting *PAR* and bw to improve the performance of the HS algorithm and eliminate the drawbacks lies with fixed values of *PAR* and *bw*, HS algorithm proposed uses variables *PAR* and *bw* in improvisation step (Step 3). *PAR* and *bw* change dynamically with generation number as shown in (Figure. 2) and expressed as follow:

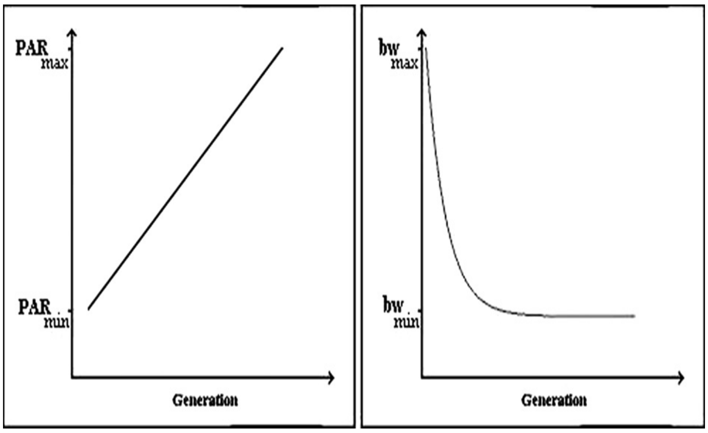


Figure 2. Variation of *PAR* and *bw* versus generation number

$$PAR(gn) = PAR_{min} + \frac{(PAR_{max} - PAR_{min})}{NI} \times gn \quad (17)$$

and

$$bw(gn) = bw_{max}.\exp(c.gn) \quad (18)$$

$$c = \frac{Ln\left(\frac{bw_{min}}{bw_{max}}\right)}{NI} \quad (19)$$

Where, *PAR* is pitch adjusting rate for each generation, *PARmin* is minimum pitch adjusting rate, PAR_{max} is maximum pitch adjusting rate, *NI* is number of solution vector generations, *gn* is generation number. *bw(gn)* is bandwidth for each generation , bw_{min} is minimum bandwidth, and bw_{max} is maximum bandwidth.

Case Study and Analysis of Optimization Results

In this paper the performance of proposed HS algorithm based CHPED problem is implemented using personal Matlab 7.1 program.

Two test systems are studied in this paper to show the effectiveness and validity of the proposed method. Test system 1 is selected from [10] and test system 2 was presented in [7]. Power outputs are in MW, heat outputs are in MWth and costs are in $ in all of the tables and figures. Economic dispatch is obtained using Harmony search algorithm proposed and the results are compared with other algorithms. The parameters of harmony search proposed used in the above tests problems are Harmony memory size (HMS) =6, Harmony memory consideration rate (HMCR) =0.95, Minimum pitch adjusting rate (PAR_{min}) =0.45, Maximum pitch adjusting rate (PAR_{Max}) =0.95, the Minimum bandwidth (bw_{min}) =0.001, and the Maximum bandwidth (bw_{Max}) =0.1.

Test System 1

The proposed test system consists of one power-only unit, 2 CHP units and the heat-only unit. The feasible operating regions of the two cogenerations units are given in (figure 3) and (figure 4) [3]. The system power demand PD and the heat demand HD are 200MW and 115MWth, respectively.

Table 1. Cost function parameters of test system1

Power only unit Unit	a	b	c	d	e	f	P_{min}	P_{Max}
1	0	50	0	0	0	0	0	150
CHP units							Feasible region	coordinates $[P^C, H^C]$
2	0.0345	14.5	2650	0.030	4.2	0.031	[98.8,0], [81,104.8]	[215,180],[247,0]
3	0.0435	36.0	1250	0.027	0.6	0.027	[44,0],[44,15.9],[40,75]	[110.2, 135.6], [125.8,32.4], [125.8,0]
Heat only units							H_{min}	H_{Max}
4	0	23.4	0	0	0	0	0	2695.2

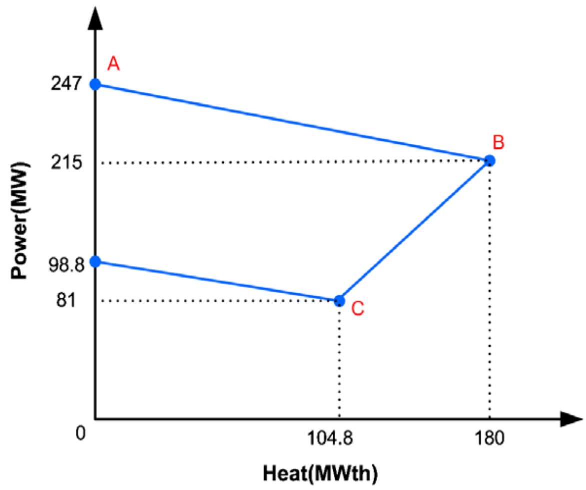


Figure 3. Feasible operation region for the cogeneration unit 2 for system1and unit 5 for system2

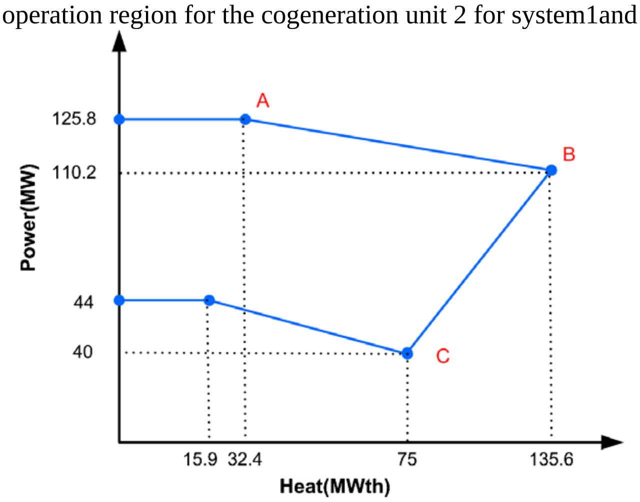


Figure4. Feasible operation region for the cogeneration unit 3 for system1 and unit 6 for system2

The results obtained by using the harmony search algorithm proposed is presented in table 2 and compared with the results obtained by various other techniques mentioned in the paper such as genetic algorithm (GA) [13], harmony search algorithm (HS) [3], augmented Lagrange Hopfield network (ALHN)[14], selective particle swarm optimization (SPSO) [12] and Proposed harmony search algorithm (EDHS)[11]. it is inferred from the table that the feasible optimum is *8526.9* $.

Table 2. Comparison the best results of HS algorithm proposed for test system1 with other methods

Output	*P1*	*P2*	*P3*	*H2*	*H3*	*H4*	*Cost*
GA[13]	*0*	*159.23*	*39.95*	*40.77*	*75.06*	*0*	*9267.2*
HS[3]	*0*	*160*	*40*	*40*	*75*	*0*	*9257.07*
ALHN[14]	*0*	*159.9994*	*40*	*39.9993*	*75*	*0*	*9257.05*
SPSO[12]	*0*	*159.7065*	*40*	*39.9097*	*75*	*0*	*9248.17*
EDHS[11]	*0*	*200*	*0*	*0*	*115*	*0*	*8606.07*
HS proposed	*2.8458*	*100.3939*	*43.1259*	*17.6107*	*76.5430*	*29.3301*	*8526.9*

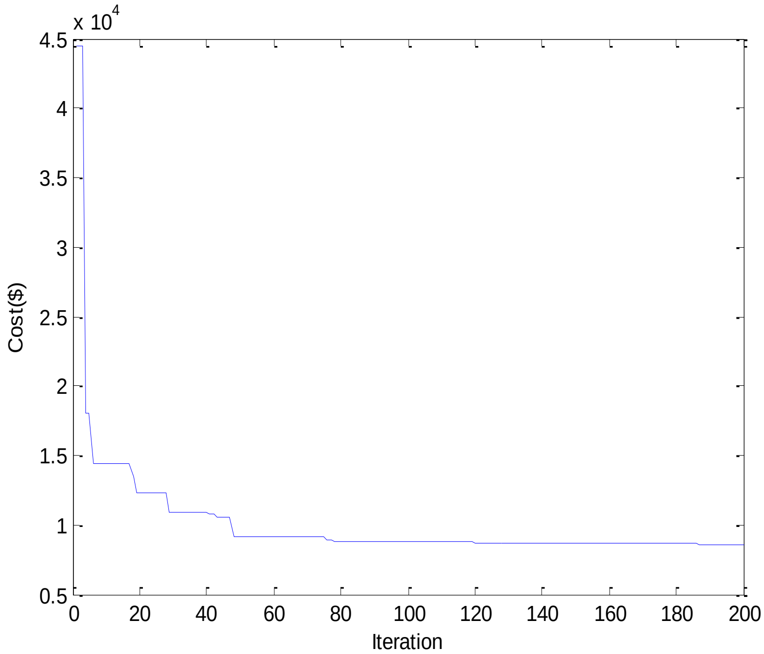


Figure 5. Convergence history the fuel cost according to the iterations of the test system 1

Test System 2

In this section a test system considering valve –point effects and transmission losses is considered to show the performance of the proposed algorithm. This system is consisted of 7 units, where units of 1-4 are power only units, units 5 and 6 are CHP units and unit 7 is heat-only unit. The cost function parameters of this case along with the feasible region coordinates of CHP units are presented in table 3.

Table 3. Cost function parameters of test system2

Power only units								
Unit	a	b	c	d	e		P_{min}	P_{Max}
1	0.008	2	25	100	0.042		10	75
2	0.003	1.8	10	140	0.04		20	125
3	0.0012	2.1	100	160	0.038		30	175
4	0.001	2	120	180	0.037		40	250
CHP unit	a	b	c	d	e	f	Feasible region	Coordinates [P^c,H^c]
5	0.0345	14.5	2650	0.030	4.2	0.031	[98.8,0], [81,104.8]	[215,180],[247,0]
6	0.0435	36.0	1250	0.027	0.600	0.011	[44,0],[44,15.9],[40,75]	110.2,135.6], [125.8,32.4], [125.8,0]
Heat only unit								
	a	b	c				H_{min}	H_{Max}
7	0.038	2.0109	950				0	2695.2

The coefficients of the network loss matrix are provided in the following. The units of B-matrix elements are 1/MW.

$$B=\begin{bmatrix} 49 & 14 & 15 & 15 & 20 & 25 \\ 14 & 45 & 16 & 20 & 18 & 19 \\ 15 & 16 & 39 & 10 & 12 & 15 \\ 15 & 20 & 10 & 40 & 14 & 11 \\ 20 & 18 & 12 & 14 & 35 & 17 \\ 25 & 19 & 15 & 11 & 17 & 39 \end{bmatrix} * 10^{-7} \quad (20)$$

The obtained optimal dispatch using HS algorithm proposed is obtained and presented in table 4 and compared with the results obtained using Artificial Bee Colony (ABC) [15], Bee Colony optimization (BCO) [7], Group Search optimization (GSO) [16] and Gravitational search algorithm (GSA) [17]. The cost convergence of the proposed algorithm is presented in figure 6. It can be observed that HS proposed provides better results as compared to the results of the previous algorithms. The feasible optimum of the system stands at *9535.3* $.

Table 4. Comparison the best results of HS algorithm proposed for test system2 with other methods

Method	P1	P2	P3	P4	P5	P6	H5	H6	H7	PL	Cost
ABC [15]	58.7117	98.5398	112.6735	209.8158	81.00	40.00	23.1014	72.2437	54.6549	2.88	10314
BCO[7]	43.9457	98.5888	112.9320	209.7719	98.8000	40.00	12.0974	78.0236	59.879	8.0384	10317
GSO[16]	45.6188	98.5401	112.6727	209.8154	94.1027	40.0001	27.66	74.9987	47.3413	0.7498	10094.2670
GSA[17]	48.7638	98.7469	112	208.5113	92.6909	40	35.9704	75	39	-	9912.6928
HS proposed	11.6692	21.7849	30.8187	43.5728	97.3660	44.2595	16.3812	75.0674	32.9191	0.003	9535.3

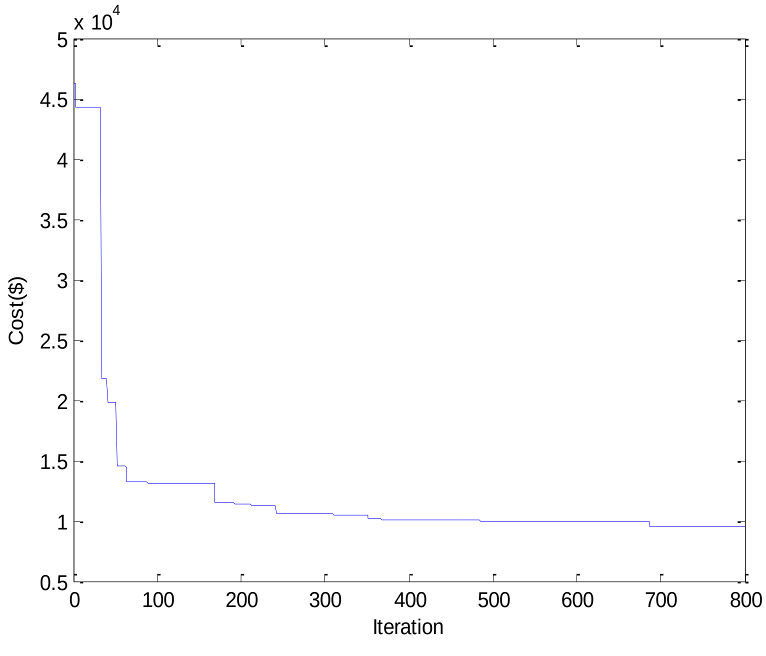


Figure 6. Convergence history the fuel cost according to the iterations of the test system 2

Conclusion

In this work harmony search algorithm proposed is used to solve CHPED problem. Two test cases with different characteristics are used to illustrate the proposed method. Valve-point effects, transmission losses, capacity limits and heat-power dependency constraints are considered in studied systems. As the results show, HS proposed has a significant decrease in cost of test system2, and test system 1, so the proposed method can be used as an alternative method for solution of CHPED problems. As future work, CHP problem can be extended by considering more practical constraints like as heat losses, ramp rates and the electricity power load balance.

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