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Intelligent Tuned Harmony Search for Solving Economic Dispatch Problem with Valve-point Effects and Prohibited Operating Zones

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ABSTRACT
Economic dispatch with valve point effect and Prohibited Operating Zones (POZs) is a non-convex and discontinuous optimization problem. Harmony Search (HS) is one of the recently presented meta-heuristic algorithms for solving optimization problems, which has different variants. The performances of these variants are severely affected by selection of different parameters of the algorithm. Intelligent Tuned Harmony Search (ITHS) is a recently developed variant, which mitigates the drawbacks of parameter initializing by maintaining a proper balance between diversification and intensification throughout the search process. The proposed method is applied to five different cases of power systems and the effectiveness, feasibility, and robustness of method is explored through the comparison with reported results in recent literature. First three case studies are systems with 3, 13, and 40-units, considering valve- point effect. The fourth and fifth cases are six and 15-generation unit taking into account generator constraints including POZs, ramp rate limit and transmission line losses which is a challenging Economic Dispatch (ED) problem due to restriction in search space. Computation results imply the efficiency of the proposed method over other optimization methods reported in recent literature, judged in terms of the objective function value and solution robustness.

KEYWORDS: Economic Dispatch, Harmony Search Algorithm, Intelligent Tuned Harmony Search, Optimization, Prohibited Operating Zones, Valve-point Effect.

1. INTRODUCTION

The objective of Economic Dispatch (ED) is to allocate the generation among all generation units to satisfy the load demand, in a way that total generation cost be the least possible amount [1]. Therefore, ED is an important optimization problem in power system operation. Optimization algorithms can be divided to two different categories, including mathematic based programming and heuristic methods. The mathematic based algorithms such as linear programming [2] and etc. were applied to ED problem with assumption that generation units have convex monotonically increasing cost functions. However, the real cost function of generation units is highly nonlinear and non-convex because of valve-point effect [3] and also discontinuous due to prohibited operating zones [4]. In contrast with previously mentioned conventional methods, heuristic methods are model independent; therefore, they can be applied efficiently to non-convex ED problem. Wide range of heuristic methods such as the Genetic Algorithm (GA) [5], Particle Swarm Optimization (PSO) and its variants [3, 6-12] ,Ant Colony Optimization (ACO) [13], Firefly Algorithm (FA) [4] and etc. are used to solve the non-linear ED problems without any restrictions on the shape of the cost curves. Harmony Search (HS) is a recently

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proposed meta-heuristic method, which try to imitate the improvisation process of music players [14]. The HS is simple in concept; easy in implementation; less in parameters and imposes fewer mathematical requirements [6, 15]. It is implemented to solve different optimization problems such as economic dispatch and satisfactory results have been reported [16]. The classical HS is good at identifying good regions in the search area within a reasonable time, but it is not efficient in performing the local search in numerical optimization applications [15]. To remove the drawbacks different methods of harmony search such as Improved HS (HIS), Global best HS (GHS) and Self Adaptive Harmony Search (SAHS) have been developed to improve the performance of the algorithm. An IHS was proposed by Mahdavi et al. [15] which dynamically updates some important parameters of the algorithm. Inspired by PSO, Omran and Mahadavi proposed GHS which generates new harmony by using best stored harmony at harmony memory [17].

Setting initial value for HS parameters can be considered as a challenging part of method. To mitigate this problem a SAHS algorithm was proposed by Wang and Huang [18], which obviate the necessity of allocating initial value to some parameters of HS. In harmony search, the optimal answers are guaranteed when the algorithm can make balance between diversification and intensification.

Diversification is needed to save algorithm form trapping in local minimal and intensification is needed for fine-tuning of the selected harmony to accelerate the convergence. Attaining to an optimal compromise between two mentioned factors has been investigated in several papers at literature, as stated in the above.

Most recently, based on the idea of balanced intensification and diversification, an Intelligent Tuned HS (ITHS) algorithm is introduced [12]. The proposed method uses the concept of despotism to improve the both intensification and diversification abilities of the algorithm [19]. Thus, the main advantage of newly developed ITHS is that algorithm can intelligently updates HS parameters to reach an optimal compromise between intensification and diversification which increase the convergence property, robustness and efficiency of method [19]. In the ITHS method, algorithm dynamically updates the value of key parameters of method regarding to the value of cost function and consequently the phenomenon of premature convergence is avoided, which happens mostly due to fixed values of parameters [15, 20]. Also, reducing the number of setting parameters makes ITHS an ideal method to coping with complex engineering optimization problems [19]. Power systems are big in size and also fuel cost function of generation units have ripples at the result of valve-point effect, which cause the number of local optima increase [21]. Therefore, an efficient algorithm should be able to reach optimal vicinity of solution at reasonable time and at the same time be secure from trapping at local minima. To validate the performance of proposed approach an extensive evaluation is done by applying the ITHS to five different ED problems. The first three problems are power systems consisting of three; thirteen and fourteen thermal unit considering valve-point effects. Other two case studies are comprised of six and fifteen generation units taking into account generator constraints including POZs and ramp rate limit with transmission line losses. Computation results imply the preference of the proposed method toward classical HS. Furthermore, effectiveness and feasibility of the proposed algorithm is proved by making comparisons with other optimization methods in literature.

2. ECONOMIC DISPATCH FORMULATION

ED problem's objective is to allocate generation to each generation unit in a manner that total generation cost be the least possible amount, which can be formulated as follows:

$$\text{Minimize } F_t = \sum_{i=1}^{N} F_i\,(P_i) \tag{1}$$

where, F_t is total generation cost, F_i the cost function of ith unit and N is number of generation units, which share the load. With taking valve-point effect into account the cost function of ith generation unit will be non-convex as follows [22]:

$$F_i = a_i P_i^2 + b_i P_i + C_i + |e_i \sin(f_i\,(P_{imin} - P_i))| \tag{2}$$

where a_i, b_i, c_i are cost coefficients of, ith unit; P_i is output electrical power of, ith unit; e_i and f_i are constants related to valve-point effect of, ith unit. The optimization problem, which is formulated by (1), should be minimized subject to following constraints:

(1) Power balance constraint: Total generation of units should satisfy the load demand. Also, in real dispatch networks, part of power is lost due to transmission loss. Thus, power balance considering system losses is written as [7]:

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

where, P_D is total load demand and P_L is the transmission loss which is a function of the unit power outputs that can be calculated using the line loss coefficients (B, B_0, B_{00}) [7].

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \tag{4}$$

(2) Generator operating limits: The output power of each generator should stay between its lower and upper generation limit (P_{imin} and P_{imax}) which can be written as [7]:

$$P_{imin} \le P_i \le P_{imax} \tag{5}$$

(3) Prohibited operating zones: Some generation units may not be able to work at some specific power zones which are known as prohibited operating zones. This limitation usually is imposed due to stability and technical concerns of units, formulated as [12]:

$$\begin{cases} P_{imin} \le P_i \le P_{i,1}^L \\ P_{i,k-1}^U \le P_i \le P_{i,k}^L \\ P_{i,z_i}^U \le P_i \le P_{i.max} \end{cases} \tag{6}$$

where, Z_i is the number, and k is the index of prohibited zone of the ith generator respectively. $P^L_{i,k}$ *and* $P^U_{i,k-1}$ are the lower and upper limits of *kth* and *(k-1)th* prohibited zone. The cost curve of a unit with valve points and one prohibited operation zone is depicted in Fig. 1.

(4) Unit ramp-rate limits: This constraint limits the increment or decrement in output power of a unit in each step. It can be written as follows [12]:

$$P_i - P_i^0 \le DR_i \quad \& \quad P_i^0 - P_i \le UR_i \tag{7}$$

where P^0_i is the previous operating point of the generator i, DR_i and UR_i are the down and up ramp rate limits of the generator i.

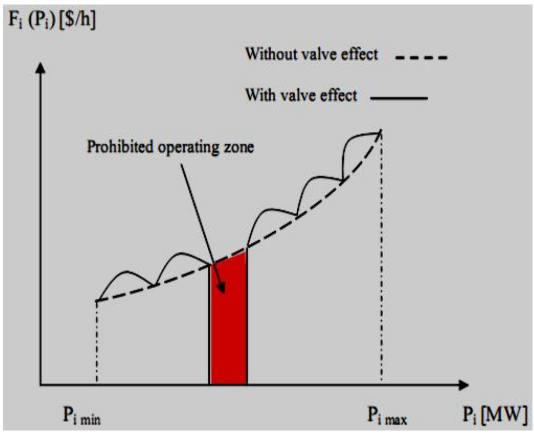

Fig. 1. Unit cost function with valve points and POZ

3. HARMONY SEARCH ALGORITHM

In one music ensemble, each music player accomplishes several steps to find the fittest musical harmony. Harmony search mimics exactly the same steps to reach best solution vectors (harmony) for an optimization problem [14]. Brief explanation of this procedure is presented in succeeding section, and further explanation can be found in [14, 15, 20, 21, 23].

3.1. Brief explanation of HS algorithm

The HS algorithm stores every selected solution in Harmony Memory (HM). HM is generally a matrix with a dimension of *HMS*N*, where HMS is harmony memory size and determines how many solution vectors can be stored in HM, and N is number of design variables. For each solution vector in HM, there is a value from objective function which is stored in matrix *f*, with the dimensions of *HMS*×1.

$$HM = \begin{bmatrix} X_1^1 & X_2^1 & \cdots & X_N^1 \\ X_1^2 & X_2^2 & \cdots & X_N^2 \\ \vdots & \vdots & \ddots & \vdots \\ X_1^{HMS} & X_2^{HMS} & \cdots & X_N^{HMS} \end{bmatrix} \quad (8)$$

$$f = \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_{HMS} \end{bmatrix}, \quad F(\overrightarrow{X^m}) = F_m, \quad \overrightarrow{X^m} = [X_1^m, X_2^m, \cdots, X_N^m];$$

$$m = 1, 2 \ldots HMS \quad (9)$$

where, F_m is the value of objective function corresponding to solution vector $\overrightarrow{X^m}$, and superscript *m*, denotes *m*-th harmony in HM. In each iteration based on three parameters (HMCR, *PAR*, *bw*), HS improvises a new harmony. HMCR is harmony memory consideration rate, which varies between 0 and 1. With probability of HMCR, a new harmony will be generated from members of HM, while (1-HMCR) is the rate of random improvisation without considering HM matrix. *PAR* is pitch adjusting rate, which varies between 0 and 1.

For a harmony that is generated from HM members, the extra improvement will be carried out with the rate of *PAR* and it will be left untouched with the rate of (1-*PAR*). Band width (*bw*), is an arbitrary value to modify selected harmony. In fact parameters of *PAR* and *bw*, are responsible for fine tuning approach of the solution vectors, which are elected from HM [15]. By elapsing of iterations, only the fittest solution vectors will be survived in HM, based on Darwinian principle. In classical HS, the setting parameters remains fixed until the end of optimization, which decrease the convergence ability of the algorithm [15]. Based on the proceeding explanations, HS can be structured in five steps as follows:

Step 1: Parameter initialization of the problem and algorithm.

Step 2: Initialization of the harmony memory (HM) with random solution vectors.

Step 3: New harmony improvisation.

Step 4: Update harmony memory according to newly improvised harmony.

Step 5: Repeat steps 3 and 4 until maximum iteration is reached.

3.2. Intelligent tuned harmony search

As stated previously, diversification and intensification has an important role on the performance of meta-heuristic algorithms. Intensification is related to local search in the vicinity of current best harmony, and diversification is about searching in the global space to avoid from trapping in local minimums [19]. Recently, Yadav et al. [19] proposed a new variant of harmony search, calling ITHS. The ITHS uses the concept of decision making based on despotism, to intelligently control the diversification and intensification. This modification is done by dividing the HM members in two parts, so calling group A and group B. Grouping rule can be expressed as follows:

for m=1:HMS
if $F_m \le F_{mean}$
$\overrightarrow{X^m} \in Group\ A$
else
$\overrightarrow{X^m} \in Group\ B$
end if
end for

F_{mean} is the mean value of the objective function for all solution vectors stored in HM. It is obvious that members of group A are existed in optimal vicinity, therefore group A is responsible for both intensification and diversification (modifying convergence property of solution). Contrary to group A, Group B's members are away from global optimal vicinity, so group B is only responsible for diversification (modifying solution's robustness by extending the search space of algorithm). Also value of *PAR* is dynamically updated, in each iteration which decreases linearly, given by (10).

$$PAR(j) = PAR_{max} - (PAR_{max} - PAR_{min}) \times (J/Maxiter)$$
$$j = 1, 2 \ldots Maxiter \quad (10)$$

where, PAR_{min} and PAR_{max} are the lower and upper boundary of *PAR*, respectively. However, in ITHS the values of PAR_{min} and PAR_{max} are fixed to 0 and 1 respectively. Thus, the problem of setting initial value for these parameters is mitigated. *Maxiter* is the maximum number of iterations and *j* is number of current iteration. The pitch adjustment for selected harmony from HM is carried out based on which group it belongs (Fig. 2). In this figure the indexes of *best* and *worst*, denotes the best and worst harmony from HM, judged in terms of objective function value. *m* is index of *m*-th decision variable which is selected randomly. UX_i and UX_m are upper limits of *i*-th and *m*-th variable.

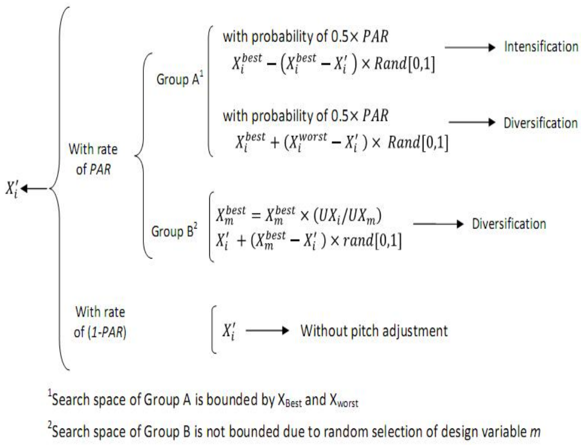

Fig. 2. Pitch adjustment process in ITHS.

4. APPLICATION OF HARMONY SEARCH TO ED PROBLEM

Fuel cost function of an ED problem with valve-point effect and POZs will be non-convex and discontinues. Nevertheless, since the HS uses stochastic random searches, derivative information of objective function is not required [23]. HS algorithm does not require initial value settings of the decision variables [7]. Therefore, any harmony which is randomly generated in step 2, is a feasible solution for problem.

According to foregoing five steps, the block diagram of HS algorithm is demonstrated in Fig. 3. In this flowchart the main part of the solution code (step 3) is depicted. *Rand* is a stochastic number, uniformly distributed between 0 and 1, and x_i^{new} is *i*th design variable of harmony vector, and *ceil* is a MATLAB order that rounds the each elements to the nearest integers greater than or equal to that element. As illustrated in Fig. 3 the output of step 3 is a new solution vector which should satisfy the equality and inequality constraints of ED problem. Considering $\overrightarrow{P^{new}}$ as the new improvised harmony, inequality constraint will be accomplished by satisfying (12) as follows:

$$\overrightarrow{P^{new}} = [P_1^{new}, P_2^{new}, \cdots, P_N^{new}] \tag{11}$$

$$P_i^{new} = \min\left(\max\left(P_i^{new}, P_i^{min}\right), P_i^{max}\right) \tag{12}$$

where, *N* is, number of units committing in ED. Index of, *i* determines the *i*th generation unit, and P_i^{min}, P_i^{max} are lower and upper generation limit of *i*th generator, respectively. After generation of each harmony (solution vector) total generation of units is compared to load demand. ΔP is a difference of generated power and load demand. In order to handle equality constraint ΔP is added to a unit (*i*th unit for example). At the next step the output of unit *i* is checked in order to not violate the generator limits and also not to work at prohibited zone. This process is iterated for other units until the ΔP is zero. Process of verifying equality constraint is demonstrated in Fig. 4.

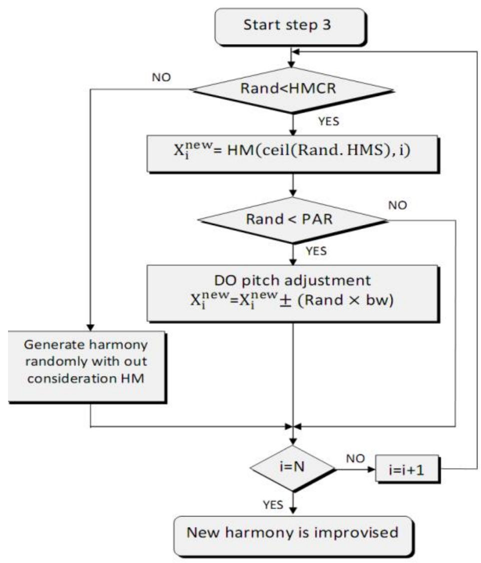

Fig. 3. Process of improvisation new harmony (step 3)

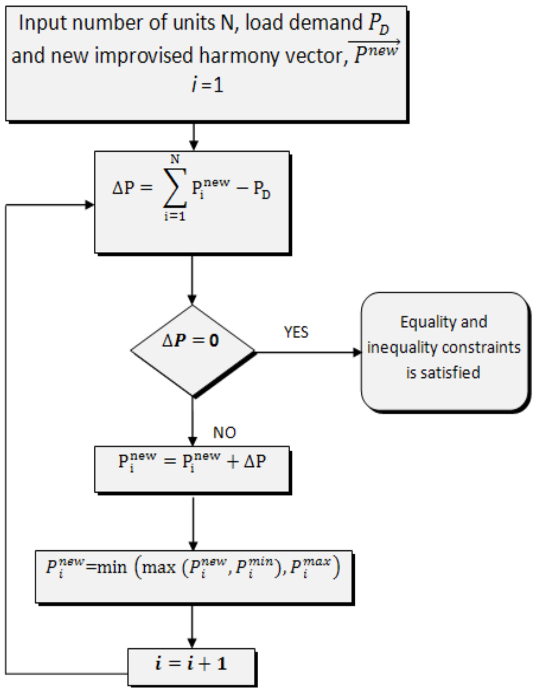

Fig. 4. Process of verifying equality and inequality constraints

5. NUMERICAL RESULTS AND COOMPARISION

In order to confirm effectiveness and feasibility of ITHS for solving ED problem, five different ED problems are investigated. The survey is done by taking into account the valve-point effect of generators for first and second and third case study. The fourth and fifth cases are six and fifteen generation unit considering generator constraint including POZs, ramp rate limit and transmission line losses. The numerical computations were executed using the MATLAB programming language. The process of setting initial value to parameters of the algorithm is done by trial and error mechanism and once that best parameters are found, 50 independent run is done to get sure from robustness of the solution.

5.1. Case study 1: 3-generating units

The first case study is system comprising three thermal units with load demand of 850 MW. Data for this system is derived from [1]. Global minimum of this system is known to be 8234.07 [24], which is obtained by most heuristic algorithms in literature. Output power of units and also the comparison of results for this case is given in Tables 1 and Table 2, respectively. This system is analyzed because of its small size, which makes it easy to describe the optimization process in ITHS. Process of grouping the solution vectors which are stored at HM (at one sample iteration) is presented at Table 3. After execution of grouping, the pitch adjustment will be carried out (if the condition is satisfied i.e., *Rand*<*PAR*). This process is presented in Table 4.

5.2. Case study 2: 13-generating units

This system contains 13 thermal units with valve-point effect and has two different levels of load demand, respectively 1800 and 2520 MW. Data of generation units is derived from [1]. The best solutions using classical HS and proposed method, for both load demand are shown in Table 5. In Tables 6 and 7 a comparison is done between the results of the ITHS and other optimization methods. It can be seen that the proposed algorithm outperforms HS and has comparable result with other optimization methods. Also, the convergence property of HS and the ITHS method is depicted in Fig. 5. It is clear that the ITHS reaches to optimal search area more effectively due to proper balance between the algorithm parameters, while the classical HS is trapped in local minima of problem. Thus, for certain problem the number of iterations is reduced for the proposed method toward classic HS.

Table 1. Output power of generators for the 3-unit test system (P_D = 850 MW)

Method	P_1 (MW)	P_2 (MW)	P_3 (MW)	Best cost ($/h)
HS	300.266743	149.733257	400	8234.071817
ITHS	300.266858	149.733142	400	8234.071753

Table 2. Comparison of the best generation cost in the 3-unit system for P_D=850MW

Method	Best cost ($/h)	Method	Best cost ($/h)
GAB [1]	8234.08	FCASO-SQP [25]	8234.07
EP [8]	8234.07	ITHS	8234.07

Table 3. Sample process of grouping HM members for 3-unit system in ITHS method (HMS=5)
**d* is a parameter for addressing each row (each harmony) of HMS matrix

d^*	HM(HMS*N)			F($/h)	Groups
	Unit1 (i=1)	Unit2 (i=2)	Unit3 (i=3)		F_{mean}=8272.5
1	302.7789	150.1816	397.0395	8272.1	A
2	302.7789	149.5125	397.7086	8264.3	A
3	398.3675	53.9239	397.7086	8281.7	B (worst)
4	302.7789	147.2211	400.0000	8280.0	B
5	302.5789	149.5125	397.9086	8260.8	A(best)

Table 4. Sample process of pitch adjustment for three-unit system in ITHS method

	i=1	i=2	i=3
*d=ceil(Rand*HMS)*	3 (Group A)	1 (Group A)	4 (Group B)
X_{new} =*HM(d, i)*	398.3675	150.1816	400.0000
Pith adjustment (*Rand <PAR*)	yes	no	yes
Applying pitch	Diversification & Intensification	Do nothing	Diversification

5.3. Case study 3: 40 generating units

This system contains 40 thermal units with valve-point effect and load demand of 10500 MW. Unit data of this system is derived from [1]. Numerical results obtained for this case study is presented in Table 8. In Table 9 a comparison is done between ITHS and other optimization methods, which reveals that the obtained solution by ITHS is better than most of the other methods reported in recent papers. 40 unit systems is large in size and has lots of local optimal Therefore this system is a formidable case to validate the robustness of solution. To validate stability of method, generation cost of system for 50 independent run is plotted in Fig. 6. It is shown that for most trials algorithm reach to same best cost. Also standard deviation, as a factor to assessment of stability, is calculated 0.1087 ($/h), which validates high robustness of the proposed method in working with large scale ED problem. It will be admissible to extend the robustness result to other valve-point cases in this paper, as for their smaller size and lower complexity.

5.4. Case study 4 and 5: six and fifteen-generating units

The case study four is a system which contains six thermal generating units. The total load demand on the system is 1263 MW. The fifth case study contains 15 thermal units with the load demand of 2630 MW. Data of both systems including cost coefficients, ramp rates, initial output power, POZs and the B-loss coefficients are adapted from [12]. Computation result for case four is given in Table 10 and for case five is presented in Table 12. Preference of ITHS toward of classical HS is confirmed in proceeding sections, thus problem is solved only for ITHS. Solution effectiveness and applicability of the proposed method is depicted by conducting a comprehensive result comparison, in Tables 11 and 13.

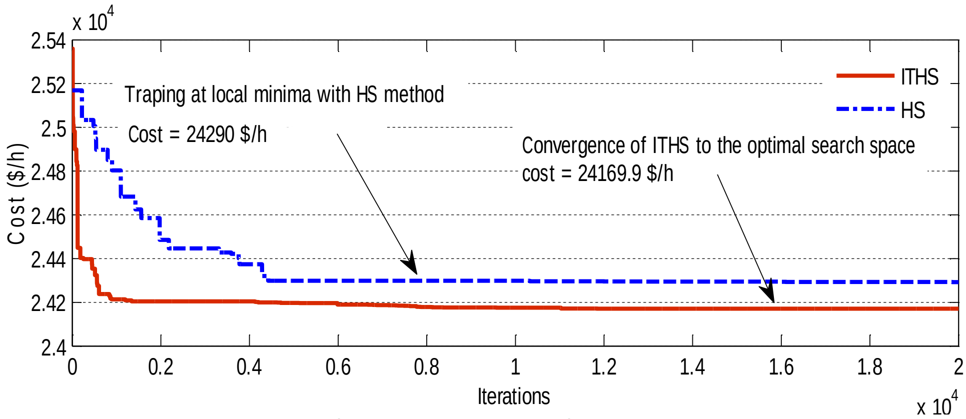

Fig. 5. Convergence property of HS and ITHS method for 13-unit system with P_D=2520 MW

Table 5. Output power of generators for the 13-unit test system

Unit	Unit generation (MW) for P_D=2520		Unit	Unit generation (MW) for P_D=1800	
	HS	ITHS		HS	ITHS
1	627.7614	628.3185	1	538.5643	628.3185306
2	299.0497	299.1992	2	224.4156	222.7493032
3	299.0837	299.1992	3	149.7582	149.59941615
4	159.5414	159.7331	4	109.9227	109.86654982
5	159.8068	159.7328	5	109.8658	109.86655003
6	159.6951	159.7331	6	109.9085	109.86655004
7	159.7535	159.7330	7	109.9535	60
8	159.6756	159.7327	8	109.9362	109.86654999
9	159.5977	159.7331	9	109.8742	109.86655005
10	74.2939	77.3993	10	77.7375	40
11	77.2256	77.3992	11	40.0112	40
12	92.2993	92.3978	12	55.0523	55
13	92.2164	87.6889	13	55.0000	55
Cost ($/h)	24174.858843	24169.921803	Cost ($/h)	17969.599253	17963.8292254

Table 6. Comparison of the best generation cost in the 13-unit system for P_D =2520 MW

Method	Best cost ($/h)	Method	Best cost ($/h)	Method	Best cost ($/h)
SA [8]	24970.91	FCASO-SQP[25]	24190.63	DSPSO–TSA [3]	24169.923
GA-SA [8]	24275.71	ACO [13]	24,174.39	EDSA [26]	24,169.92
EP-SQP [8]	24266.44	MGSO[27]	24173.8886	**HS**	**24174.858843**
PSO-SQP [8]	24261.05	HGA [5]	24169.92	**ITHS**	**24169.921803**
CASO [25]	24212.93	TSA [3]	24171.211		

Table 7. Comparison of the best generation cost in the 13-unit system for P_D =1800 MW

Method	Best cost ($/h)	Method	Best cost ($/h)
CEP [1]	18048.21	MGSO [27]	17963.8312
PSO [8]	18030.72	CASO [25]	17965.15
MFEP [1]	18028.09	FCASO-SQP [25]	17964.08
IFEP [1]	17994.07	PSO-TVA [28]	17963.879
EP–SQP [8]	17991.03	QPSO [29]	17969.01
DEC-SQP [30]	17963.94	SHDE [31]	17963.89
HMAPSO [32]	17969.31	TSAGA [33]	17963.94
QPSO [29]	17969.01	FA [4]	17,963.83
ST-HDE [34]	17963.89	HS	17969.599253
FAPSO-VDE [11]	17963.82	ITHS	17963.829225

Table 8. Output power of 40-unit system (P_D=10500 MW)

Unit	Generation (MW)	Unit	Generation (MW)	Unit	Generation (MW)	Unit	Generation (MW)
1	110.8196	11	94.0000	21	523.2794	31	189.9904
2	110.8196	12	94.0000	22	523.2794	32	189.9997
3	97.4855	13	214.7527	23	523.2794	33	189.9996
4	179.7330	14	394.2793	24	523.2794	34	165.1401
5	87.8006	15	394.2779	25	523.2794	35	199.8503
6	140.0000	16	394.2501	26	523.2794	36	194.1707
7	259.6103	17	489.2794	27	10.0000	37	109.9702
8	284.5995	18	489.2794	28	10.0000	38	109.9913
9	284.5995	19	511.2794	29	10.0000	39	109.9862
10	130.0000	20	511.2794	30	87.8007	40	511.2794

Table 9. Comparison of the best generation cost for 40-unit system

Method	Best cost ($/h)	Method	Best cost ($/h)	Method	Best cost ($/h)
IABC [35]	121491.2751	IABC-LS [35]	121488.7636	DEC-SQP [30]	121741
QPSO [29]	121448.21	TSAGA [33]	121463.07	DE/BBO [36]	121420.9
HMAPSO [32]	121586.9	ACO [37]	121532.41	HS	121507.917018
SOHPSO [38]	121501.14	FCASO [39]	121516.47	ITHS	121416.652640
FAPSO [40]	121712	CSO [41]	121461.6707		

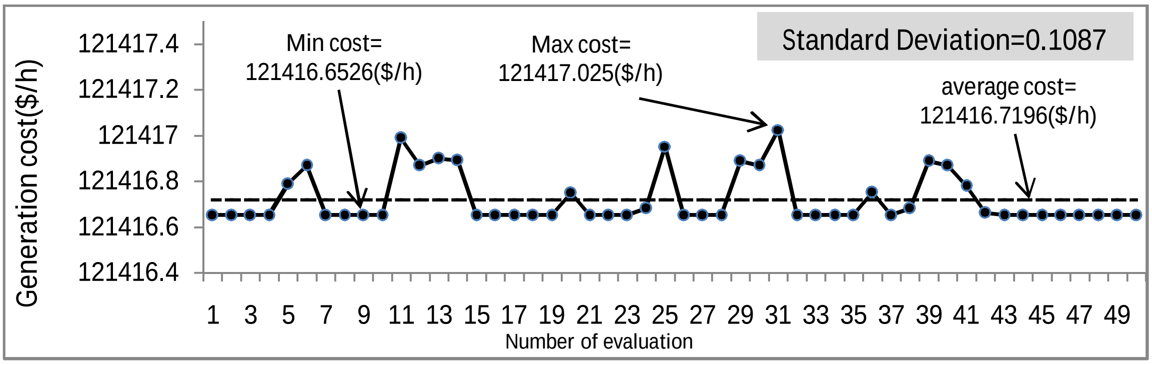

Fig. 6. Total fuel cost values obtained for 50 trials (case 3- ITHS method)

Table 10. Output power of units for the 6-unit test system (with POZ-ramp rate & line loss)

unit	Best	Worst
1	449.6700	444.731
2	171.1967	171.523
3	260.0433	261.421
4	140.4507	141.671
5	168.1951	170.609
6	85.8554	85.4671
Total generation	1275.4112	1275.4221
Total loss	12.4175	12.4195
Cost($/h)	15442.887	15443.1458

Table 11. Comparison of the best generation cost in the 6-unit system

Method	Best cost ($/h)	Method	Best cost ($/h)	Method	Best cost ($/h)
GA [12]	15459	MTS [42]	15450.06	CPSO [6]	15446
NCS [43]	15447.00	TS [38]	15451.63	SOHPSO [38]	15446.02
BCO [44]	15450.031	MPSO [10]	15443.0925	HHS [45]	15449
PSO [12]	15450	DHS [46]	15449.8996	ITHS	15442.887
IPSO [9]	15444	DHS1[46]	15449.7674		

Table 12. Output power of units for 15-unit test system (With POZ-ramp rate & line loss)

Unit	Best	Worst	Unit	Best	Worst
1	454.8399	454.9828	10	157.9175	150.6390
2	379.9939	379.6045	11	79.7113	79.9135
3	130.0000	130.0000	12	79.2993	79.9307
4	130.0000	130.0000	13	25.0001	27.3224
5	169.9483	169.9972	14	16.0608	18.0629
6	459.9727	459.9957	15	15.0000	16.6049
7	430.0000	430.0000	Total generation	2659.6442	2659.1845
8	79.9210	77.6187	Total loss	29.6492	29.1897
9	51.9794	54.5122	Cost($/h)	32694.73561	32698.9714

Table 13. Comparison of the best generation cost in the 15-unit system

Method	Best cost ($/h)	Method	Best cost ($/h)	Method	Best cost ($/h)
GA [12]	33113	MTS[42]	32716.87	CPSO[6]	32834
NCS [43]	32708	DSPSO–TSA [3]	32715.06	SOHPSO [38]	32751.39
BCO [44]	32714.2658	TS [38]	32917.87	PSONCS [43]	32708
PSO [12]	32858	FA [4]	32704.4501	ITHS	32694.73561
IPSO [9]	32709	MPSO[42]	32738.4177		

6. CONCLUSIONS

This paper has proposed the application of harmony search algorithm, comprising the most recently proposed intelligent tuned harmony search to solve ED problem with non-convex and discontinues fuel cost function. The main advantage of newly developed ITHS method is that, it can intelligently make an optimal balance between diversification and intensification in search process. This is accomplished by automatically selecting the proper pitch adjusting strategy. Consequently, convergence and solution robustness is improved and also parameter setting is mitigated. Thus, algorithm is an ideal method to solve complex non-convex ED problem. The performance of HS and ITHS were tested for five different case studies. First three cases are power systems with consideration of valve-point effect which results in a non-convex cost function. Last two cases are systems with regarding POZs and losses which is a challenging ED problem due to restriction in search space. The obtained results reveal that the ITHS method has an evident preference toward classical harmony search, judged in terms of solution effectiveness and value of objective function. Also, robustness of the method was successfully analyzed by regarding a large scale power system (40-unit system).Furthermore, the results indicate that the ITHS method converged to lower generation cost, when comparing to other optimization methods which are available in recent literature.

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