Improved Dynamic Harmony Search Optimization for Economic Dispatch Problems with Higher Order Cost Functions

Boudjella Houari^{1,*}, Laouer Mohammed², Bouzeboudja Hamid¹, Ayad Ahmed Nour El Islam³,
Mkattiri Sara⁴, Saad Abdallah⁴

¹Department of Electrical Engineering, University of Sciences and Technology of Oran-Mohamed-Boudiaf (USTO-MB), Algeria

²Department of Science and Technology, SALHI Ahmed University Centre, Algeria

³Department of Electrical Engineering, KASDI Merbah University, Algeria

⁴Department of Electrical Engineering, National School of Electricity and Mechanics, Hassan II University, Morocco

*Corresponding Author: houari.boudjella@univ-usto.dz

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Abstract This paper presents a modified harmony search algorithm with dynamically varying bandwidth, named improved dynamic harmony search algorithm (IDHSA) for economic load dispatch (ELD) problems with higher cost functions. The economic load dispatch problem aims to schedule power outputs of the generating units to meet the system load demand at minimum cost while satisfying the equality and inequality constraints. In the IDHS algorithm, the key difference from the conventional HS algorithm is that bandwidth (BW) operator changes dynamically at every iteration. The IDHS algorithm is tested with two different cases of power systems without and with transmission losses. The obtained results prove the accuracy and the effectiveness of the IDHS algorithm in determining the best solution compared than other optimization methods recently published in the literature.

Keywords Economic Dispatch, Cubic Cost Function, Power System Control, Harmony Search Algorithm

1. Introduction

An electric power system consists of generation, transmission and distribution utilities to enhance electrical power to the consumers. Economic dispatch is the short-term determination of the optimal output power of generators to meet the system load and operate the generators at the lowest fuel cost [1]. The solution accuracy of economic dispatch problems is associated with the precision of the fuel cost curve parameters [2]. In the classical ED problem, the cost function of active power

generation is approximated presented as a second-order polynomial. But because of the high nonlinearity and non-smooth of the real input-output characteristics of the generating units, another cost function model is used by applying cubic cost function in which outputs enter linearly, as quadratics, and to the third degree [3]. This type of function is the most correct because it yields appropriately shaped average and marginal cost curves [4]. A third-order polynomial model is more precisely to reflect the real response of thermal generators [5]. Several kinds of research prove that cubic cost function is more practical than a quadratic cost function to express the operating cost [6]. In the recent years, the solution of ED problem with higher-order cost function has captured the attention of various researchers using diverse algorithms include various mathematical procedures such as PSO algorithm suggested in [5], genetic algorithm (GA) in [6]. Al-sumait et al. implemented a pattern search (PS) algorithm in literature [7] to solve ED problems with a cubic fuel cost function. In reference [8], a firefly algorithm (FA) is applied to solve ED problems with CCF. Simulated Annealing algorithm (SA) is proposed in [9], Quantum-PSO developed by F. Parvez Mahdi et al. in [10], a novel MVMOS technique in [11], Grasshopper Optimization Algorithm (GOA) is proposed in [12]. Modified Firefly Algorithm with Levy Flights and Derived Mutation (MFA-LF-DM) in [13] is developed to solve single-objective dynamic ED with CCF. Artificial Bee Colony (ABC) [14] is implemented for combined economic and emission dispatch problems. Gravitational Search Algorithm is provided in [15] to solve a multi-objective dispatch problem.

Harmony search (HS) algorithm is one of the most popular evolutionary algorithms originally invented by

Geemet al [16], which draws inspiration from the musical process to attain an agreeable harmony. HS takes some major advantages compared with other metaheuristics, such as EP, GA, DE and tabu search (TS), which is simple in concept and structure, converges quickly to the optimum and easy to implement on optimization problems [17, 18]. In the last decade, the harmony search algorithm (HSA) has widely used to solve kinds of optimization problems [19, 20]. In this work, to prove the effectiveness and the robustness of the proposed method, the cubic cost function economic dispatch problems (CCFED) of two different cases grouped as lossless and lossy test systems have been solving and the results have been compared with some other optimization techniques reported in recent literature. The remainder of the paper is organized as follows: Section. 2 provides descriptions and formulations of ELD problems with cubic fuel cost functions. Whereas the harmony search algorithm is briefly discussed in section. 3. Section. 4 includes an introduction to the IDHS algorithm and its implementation to CCFED problems. Simulation, results, and analysis of the findings are presented in section.5. Finally, the conclusion of the work done in the paper is given in section 6.

2. Descriptions and Formulations of CCFED Problems

In the CCFED we seek

- a) to minimize the total cost of generating real power, which is written as [2, 22]:

$$\min F = \sum_{i=1}^N F_i(P_i) \quad i \in [1, N] \quad (1)$$

where

$$F_i(P_i) = a_i \times P_i^3 + b_i \times P_i^2 + c_i \times P_i + d_i \quad (2)$$

Where, P_i is the real power generation of unit i in (MW), N number of generators in the network, a_i, b_i, c_i and d_i are the fuel cost coefficients of the unit i .

- b) To minimize the transmission losses

$$\min P_L = \sum_{i=1}^N \sum_{j=1}^N P_i B_{ij} P_j + \sum_{i=1}^N B_{0i} P_i + B_{00} \quad (3)$$

Equation (2) is subject to the equality and inequality constraints.

A. Equality constraints

$$P_T - P_D - P_L = 0 \quad (4)$$

Where P_T, P_D and P_L are the total power generated, power system demand and total power loss respectively.

B. Inequality constraints

The output power produced by generators has particularly limited by lower and higher powers. Equation

(5) shows the relation of inequality constraint.

$$P_i^{\min} \leq P_i \leq P_i^{\max} \quad i = 1, 2, \dots, N \quad (5)$$

3. Basic Harmony Search Algorithm HSA

The basic HS algorithm works as follows [16-18]:

Step 1. (Initialization). Set parameters of HS, The main parameters of the HS method include [16]:

- Harmony memory size (HMS), where the population is memorized.
- Pitch adjusting rate (PAR) for a new generated harmony, where $PAR \in [0, 1]$,
- Harmony memory considering rate (HMCR), where $HMCR \in [0, 1]$,
- Bandwidth (BW) for pitch adjustment, number of improvisations (NI) and number of maximum iterations (Nmax).

$$\text{Minimize } f(x) \quad (6)$$

Subject to

$$LB_i \leq x_i \leq UB_i \quad i \in [1, N] \quad (7)$$

Where $f(x)$ is the objective function, x_i is the solution vector of the HMS, LB_i and UB_i are the lower and upper values of x_i .

Step 2. Harmony memory initialization. HM is a set of decision variables [17], the initial harmony memory is randomly generated by using (8):

$$x_i^j = LB_i + \text{rand}() \times (UB_i - LB_i) \quad (8)$$

Where $j = 1, 2, \dots, HMS$ and $\text{rand}()$ is random number, uniformly distributed within the range $[0, 1]$.

Mathematically, the HM matrix can be represented by the following expression:

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \dots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \dots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \dots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \begin{matrix} \rightarrow f(x^{(1)}) \\ \rightarrow f(x^{(2)}) \\ \vdots \\ \rightarrow f(x^{(HMS-1)}) \\ \rightarrow f(x^{(HMS)}) \end{matrix} \quad (9)$$

Step 3. Improvise a new harmony as follows:

A novel solution vector $x_i^{\text{new}} = (x_1^{\text{new}}, x_2^{\text{new}}, \dots, x_N^{\text{new}})$ is generated based on the main HS operators HMCR, PAR and BW. Such operators are considered in production of a new harmony as the following [18]:

$$x_i^{\text{new}} \leftarrow \begin{cases} x_i^{\text{new}} \in \{x_i^1, x_i^2, \dots, x_i^{HMS}\}, & \text{with probability HMCR} \\ x_i^{\text{new}} \in X_i & \text{otherwise } i = 1, 2, \dots, N \end{cases} \quad (10)$$

Pitch adjusting decision:

$$x_i^{new} \leftarrow \begin{cases} \text{Yes} & \text{with probability } PAR \\ \text{No} & \text{with probability } (1 - PAR) \end{cases} \quad (11)$$

A new solution vector x_i based on the disturbance principle can be generated as follows:

$$x_i'^{new} = x_i^{new} + 2 \cdot \text{rand}() \times BW - BW \quad (12)$$

Step 4. Update the HM vector, $x_i^{new} = (x_1^{new}, x_2^{new}, \dots, x_N^{new})$ as $x_{worst} = x_{new}$ if $f(x_{new}) < f(x_{worst})$.

Step 5. (Checking the stopping criterion): Repeat steps 3 and 4 until the stopping criterion (normally, when the maximum number of improvisations is reached).

A simplified flowchart of the HS method is demonstrated in Fig1.

Figure 1. A simplified flowchart of the HS algorithm.

4. Improved Dynamic Harmony Search Algorithms (IDHSA)

4.1. The Motivation of the IDHS Algorithm

To enhance the behavior and the convergence speed of the original HSA, many variants of the HS method based on parameters setting have been studied with incorporating some modifications to the main operators of HSA (i.e., PAR, HMCR, and BW), such as the variations proposed in the literature [25-29]. The PAR and BW parameters, deciding the precision of the solution. If we choose a small BW and low PAR values, the convergence speed of HSA becomes slowly and the fine-tuning of solution vectors will increase. Furthermore, if we choose a bigger PAR value with a wide BW value in the early generation, HSA will converge quickly to the best solution. Therefore, is very necessary that PAR and BW were dynamically adjusting at every iteration.

In [30], Kalivarapu et al have developed a new modification of harmony search algorithm, with bandwidth varying dynamically at every iteration to improve the performance and complexity of existing HSA. The principle behind this idea is to use a wider BW to search in the entire domain and dynamically adjust the BW towards the optimal solution.

4.2. New Parameter of BW

In this subsection, the modified HS algorithm with dynamic BW operator will be studied. Dynamic BW (DBW) is represented as a decreasing function of the current generation and number of maximum iterations specified for the problem, i.e. in the initial stages of this algorithm, BW is dynamically modified by maintaining a higher value and gradually decreasing by a low value to ensure close convergence of the optimal solution [30].

The selection of termination condition depends on the desired precision level of solution [31]. According to the criteria mentioned above, we find that the equation of a low-pass filter is approximately close to the requirement.

The new BW equation can be expressed as follows:

$$BW(i) = \frac{h}{1 + \gamma \cdot \left(\frac{i}{N_{\max}}\right)^{\alpha}} \quad (13)$$

Where, h and γ are the constant parameters depend on the limit values of BW. To satisfy the above-mentioned criteria, the exponent α must be greater than 1. 'i' and 'Nmax' are the current iteration and total number of iterations.

According to [30], a reasonably fair result can be obtained when minimum value of BW (BWmin) should be very small, generally $\sim 0.1\%$ of the range of decision variables. While, BWmax is assumed to 5~10% of the

range of decision variables. The constant γ is evaluated with the logarithmic decremental function as follow [30]:

$$\gamma = b_1 \times \ln\left(\frac{BW_{\max}}{b_2 \times BW_{\min}}\right) \quad (14)$$

Where b_1 and b_2 are the constants and their numerical values are experimentally evaluated in [30, 31], the best values of b_1 and b_2 that gives a minimum BW value ensures precise and fast convergence towards the optimal solution are considered to be 50 and 100, respectively (best values).

For the problems having low decision variables (≤ 8 variables), Eq. (13) is more efficient to compute dynamic BW. For highly complex optimization problems, the best solution is found by modified (13) to a discontinuous adaptative dynamic BW function [30]. The proposed DADBW function is expressed as:

$$BW(i) = \begin{cases} BW(i) = \frac{h}{1 + \gamma \cdot \left(\frac{i}{N_{\max}}\right)^{\alpha}} & ; i < pivot \\ BW_{\min} & ; i \geq pivot \end{cases} \quad (15)$$

Where, 'pivot' decides the optimum point where the BW changes (generally $N_{\max}/2$).

4.3. Implementation of IDHSA to CCFED Problems

Based on the corresponding improvement methods, the proposed IDHS algorithm process is shows below:

Step 1. Specify the generator cost coefficients (a_i , b_i , c_i and d_i), total number of generator units (N), specify $P_i^{\max}$ and $P_i^{\min}$ of all generators and load demand P_D .

Initialize the parameters of IDHS algorithm (HMS, HMCR, PAR, $BW_{\max}$, $BW_{\min}$, NI, $N_{\max}$ and Pivot).

Step 2. Initialize HM matrix with size (HMS $\times$ N). The initial HM is randomly generating as follow:

for j=1 to HMS **do**

for i=1 to N **do**

$$HM(i, j) = P_i^j = P_i^{\min} + rand() \times (P_i^{\max} - P_i^{\min}) \quad (16)$$

if $\sum_i^N P_i < P_D$, Add an amount ε

$\varepsilon \leftarrow \left| \sum_i^N P_i - P_D \right|$ to P_i^{new} that doesn't violate $P_i^{\max}$,

such as $P_i^{new} \leftarrow \min(P_i^{new} + \varepsilon, P_i^{\max})$

else if $\sum_i^N P_i > P_D$, Subtract an amount ε

$\varepsilon \leftarrow \left| \sum_i^N P_i - P_D \right|$ to P_i^{new} that doesn't violate $P_i^{\min}$,

such as $P_i^{new} \leftarrow \max(P_i^{new} - \varepsilon, P_i^{\min})$

Figure 2. Constraints handling used IDHS algorithms

To not violate the generator limits and not to work at the prohibited zone after the generation of each solution vector, the total generation of units is compared to load demand. Fig. 2 shows the process of verifying the equality constraint used in the IDHS algorithm. This process is iterated for other units until the ε is zero.

Step 3. Calculate the fitness value for each harmony vector in the HM matrix using (5). The HM matrix is represented as follow:

$$HM = \begin{bmatrix} P_{G1}^1 & P_{G2}^1 & \dots & P_{GN-1}^1 & P_{GN}^1 \\ P_{G1}^2 & P_{G2}^2 & \dots & P_{GN-1}^2 & P_{GN}^2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ P_{G1}^{HMS-1} & P_{G2}^{HMS-1} & \dots & P_{GN-1}^{HMS-1} & P_{GN}^{HMS-1} \\ P_{G1}^{HMS} & P_{G2}^{HMS} & \dots & P_{GN-1}^{HMS} & P_{GN}^{HMS} \end{bmatrix} \begin{matrix} \rightarrow f(P_G^{(1)}) \\ \rightarrow f(P_G^{(2)}) \\ \vdots \\ \rightarrow f(P_G^{(HMS-1)}) \\ \rightarrow f(P_G^{(HMS)}) \end{matrix} \quad (17)$$

Step 4. Generate a new harmony solution as described in step 3 (section 3), with bandwidth (BW) is dynamically updating using (15). The new harmony improvisation process is depicted by the flowchart shown in Fig.3.

Step 5. Update the HM vector and calculate the fitness value $f(P_G)$, $P_i^{new} = (P_1^{new}, P_2^{new}, \dots, P_N^{new})$ a $P_i^{new} = P_i^{worst}$ if $f(P_i^{new}) < f(P_i^{worst})$, exclude P_i^{worst} .

Step 6. If the maximum number of improvisations is reached, go to Step 7; otherwise, repeat steps 4-5.

Step 7. Print the optimal value of real power generation of generators and total cost of generation.

Fig. 4 shows and explains the detailed phases of simulations to solve the CCFED problem using IDHSA. After the generation of each harmony (solution vector), the total generation of units is compared to load demand P_D .

Figure 3. Process of improvisation new harmony of IDHS algorithm

Figure 4. Pseudo code of IDHS algorithm to CCFED problems

5. Results and Discussion

To evaluate the efficiency of the proposed IDHS algorithm, the above algorithm is first applied to a CCFED problem with a 3-units system (Wollenberg's power network) [32] and 5-units systems [5] and then to Liang's power network [24]. It should be noted that the tow test systems are lossless in the first case while the power losses are considered in the second case. For both grouped cases studied, the algorithm of IDHS is run 20 independent trials; the software proposed was implemented in Matlab (R2017a) and executed on a PC with an Intel (R) Core i3-3110 CPU processor (2.40 GHz), 4 Go RAM and MS Windows 10. For conducting the test, the parameters of IDHS algorithm for all test systems are given as follows: HMS = 5, HMCR = 0.85, PAR = 0.3, BW_{min} =0.01, BW_{max} = 0.5, NI = 50 and the max tries (N_{max}) is set at 3×10^4 . The required data with cubic cost function coefficients of all test systems are given in Tables 1, 2 and 3.

Table 1. Data Parameters of 3 units System (Wollenberg's Network) [5, 32]

Unit	a_i	b_i	c_i	d_i	P_{min}	P_{max}
1	1.27e-07	9.68e-04	6.950	749.55	320	800
2	6.45e-08	7.375e-04	7.051	1285	300	1200
3	9.98e-08	1.04e-03	6.531	1531	275	1100

Table 2. Data Parameters of 5 units System [5]

Unit	a_i	b_i	c_i	d_i	P_{min}	P_{max}
1	1.27e-07	9.68e-04	6.950	749.55	320	800
2	6.45e-08	7.375e-04	7.051	1285	300	1200
3	9.98e-08	1.04e-03	6.531	1531	275	1100
4	1.27e-07	9.68e-04	6.950	749.55	320	800
5	6.45e-08	7.375e-04	7.051	1285	300	1200

Table 3. Data Parameters of 3 units system (Liang's network) [24]

Unit	a_i	b_i	c_i	d_i	P_{min}	P_{max}
1	3.33e-6	-2.6429e-3	5.10238	11.2	100	500
2	3.33e-5	-3.0571e-2	13.01	-632	100	500
3	-1.77e-7	3.0845e-4	4.28997	147.144	200	1000

5.1. Case 1: Lossless Test Systems

The IDHS algorithm is applied to solve the CCFED problem with 3-generator [32] and 5-generator systems [5] for the load power system respectively as 2500 (MW) and 1800 (MW).

The best generation schedule of 3 generating units along with the total cost obtained by proposed IDHS over 20 runs are compared with GA [5], PSO [5], SA [9], and FA [8] in Table 4.

The optimal total cost obtained by the proposed IDHS algorithm is 22729.3019 \$/h. In this case study, the results

without losses are compared with as seen from table 4, that the proposed IDHS is better compared to GA [5], PSO [5] and SA [9] in terms of provided better solution, with the exception of FA [8] generated the best solution of 22728 \$/h. The computational time of IDHSA is faster (0.258 s).

Fig. 5 shows the convergence speed of the IDHS algorithm to CCFED minimization for Wollenberg's power system [32]. IDHS has been trapped into local optimum at about 349 iterations.

Table 4. Comparison of CCFED results for 3-units system [23]

Unit	GA [5]	PSO [5]	SA [9]	FA [8]	Proposed IDHSA
1	725.02	724.99	725.01284	729.0682	724.97925
2	910.19	910.15	910.18417	906.8021	910.17743
3	864.88	864.85	864.80299	864.1315	864.84330
Total Power (MW)	2500	2500	2500	2500	2500
Total Cost (\$/h)	22730.14	22729.35	22729.32458	22728	22729.301959
CPU Time (sec)	-	-	-	-	0.258

Figure 5. Convergence property of CCFED minimization for Wollenberg's Network [5, 32] using IDHSA with $P_D = 2500$ MW

Figure 6. Best generation schedule of three generating units obtained by comparative methods for $P_D = 2500$ MW.

The loss coefficient matrix B for the Liang's network system[24] is:

$$B = 1 e - 4 \times \begin{bmatrix} 0.75 & 0.05 & 0.075 \\ 0.05 & 0.15 & 0.10 \\ 0.075 & 0.10 & 0.45 \end{bmatrix}$$

The optimal power output of three generating units obtained by each algorithm is offered in Fig. 6. The best

dispatch and best fuel cost solution obtained by IDHS are compared with those given by GA [5], PSO [5], and FA [8] in Table 5. Notably, the optimal cost value obtained is 18610 \$/h, it is achieved by FA [8], while the best cost obtained by the IDHS algorithm is 18610.375 \$/h, which is the comparatively less than other methods. Also, the computational time of IDHSA is very fast (0.2736 s).

Table 5. Comparison of CCFED results for 5-units system [5]

Unit	GA [5]	PSO [5]	FA [8]	Proposed IDHSA
1	320.00	320.00	327.8004	320.00
2	343.74	343.70	341.9890	343.71005
3	472.60	472.60	460.4127	472.57991
4	320.00	320.00	327.8004	320.00
5	343.70	343.70	341.9890	343.71003
Total Power (MW)	1800	1800	1800	1800
Total Cost (\$/h)	18611.07	18610.40	18610	18610.3755
CPU Time (sec)	-	-	-	0.2736

Figure 7. Convergence property of CCFED minimization for 5 units system [4] using IDHSA with PD = 1800 MW

Figure 8. Best generation schedule of five generating units obtained by comparative methods for PD = 1800 MW

Fig. 7 shows the behavior of the IDHSA convergence visualized in terms of fuel cost against 3.104 generations for the load demand of 1800 MW. The IDHS algorithm converges quickly to the best cost value; at about 813 iterations. The best generation schedule of five generating units obtained by every algorithm is illustrated in Fig. 8.

5.2. Case 2: Lossless Test Systems

The second case study covers three thermal units [24] with an overall load demand of 1400 MW, with considering transmission losses. In case, the IDHS algorithm is applied to solve the CCFED problem for Liang's network system [24].

The obtained results with losses by the proposed IDHS algorithm are compared with the best solutions of SA [9], DP [24] and TLBO [33] methods in Table 6. We can see from Table 6 that the minimum fuel cost of the proposed IDHS (6640.2776 \$/h) is comparatively lower than any other methods except for the TLBO [33] (6639.13 \$/h) performs significantly better than IDHS, but the results are competitive. IDHS algorithm gives less power losses (43.3984 MW) compared to the mentioned methods while satisfying the equality and inequality constraints. The computational time gives by the IDHS algorithm is

(17.9345 s).

Table 6. Comparison of CCFED results for Liang's network system [24] for $P_D = 1400$ MW

Unit	SA [9]	DP [24]	TLBO [33]	Proposed IDHSA
1	359.7034	360.2	362.830	359.9849
2	406.5985	406.4	100.000	407.4036
3	677.1375	676.8	1000.000	676.0100
Total Power (MW)	1400	1400	1400	1400
Power loss (MW)	43.4395	43.4000	62.83	43.3984
Total Cost (\$/h)	6642.6628	6642.26	6639.13	6640.2776
CPU Time (sec)	-	-	-	17.9345

As observed from Tables 4-6, the power output of each unit lies within the minimum and maximum generator capacity limits and satisfies the power balance constraint.

Fig. 9 shows the best generation schedule of three generating units [24] obtained by comparative algorithms. Fig. 10 clearly shows that power losses represent only 3.0998% of the total power generation as with the cost of losses.

Figure 9. Best generation schedule of three generating units obtained by comparative methods for $P_D = 1400$ MW

Figure 10. Transmission power losses percent % of three generating units [24]

6. Conclusions

In this paper we have introduced a new approach to solve CCFED problems based on the modified harmony search algorithm applied in two different cases as lossless and lossy test systems. The proposed IDHS algorithm has justified its robustness, versatility and high probability for CCFED problems; IDHSA has also achieved the best total cost with high feasibility and efficiency for 3-units [23], 5-units systems [4] and Liang's network system [15] for the load power system respectively as 2500 (MW), 1800 (MW) and 1400 (MW). The comparison of simulation results with those obtained by other methods such as DP, GA, PSO, SA, FA, and TLBO, prove the superiority of the IDHSA over them. The numerical findings confirm that the IDHS algorithm can provide better solutions with the lowest computation time than other different metaheuristic methods, and successfully improve the efficiency of the CCFED problems.

In the future, the authors plan to introduce it to other kinds of optimization issues, such as multi-objective ED problems with valve point loading effect and many complex constraints, dynamic ED problems, large-scale ELD problems integrated renewable energy sources.

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