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Solving Short-Term Cascaded Hydrothermal Scheduling Problem Using Modified Cuckoo Search Algorithm

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Abstract

This paper presents a modified cuckoo search algorithm (MCSA) for solving short-term cascaded hydrothermal scheduling (ST-CHTS) problem. The short-term cascaded hydrothermal scheduling is to determine the optimal operation for thermal plants and a cascaded reservoir system while satisfying all constraints including electrical constraints of both hydro and thermal plants and hydraulic constraints of reservoirs. The MCSA has been developed by modifying the search strategy via Lévy flights to improve the performance of the conventional cuckoo search algorithm. The proposed method has been widely and successfully applied to many optimization problems in engineering fields; however, this is first time employed to search for the optimal solution of the ST-CHTS problem. The proposed method has been tested on two systems where thermal plants with nonconvex fuel cost function and a cascaded reservoir system are taken into account. The result comparison from the MCSA compared to other methods reported in the literature has revealed that the proposed MCSA is very efficient for solving the ST-CHTS problem.

***Keywords**: Modified Cuckoo search algorithm; cascaded hydropower plants; Lévy flights*

1. Introduction

A power system mainly consists of thermal plants and hydropower plants to supply electricity to load demand. Therefore, optimal operation of a hydrothermal system is very important once the electricity generation cost is minimized. One of the problems regarding to hydrothermal scheduling problem is short-term cascaded hydrothermal scheduling problem where the main task is to determine the power output of each available power plant so that the generation fuel cost is minimized over an optimization interval such as a single day and a week while electrical and hydraulic constraints including power balance, limits on generations, water discharge rate, and as well as reservoir storage limits are exactly met [1].

In recent decades, several artificial intelligence algorithms, such as genetic algorithm (GA) [2-3], two-phase neural network [4], evolutionary programming technique (EP) [5], particle swarm optimization (PSO) [6-7], differential evolution [8-9], and clonal selection algorithm (CSA) [10] have been widely and successfully applied for solving the ST-CHTS problems where quadratic and/or nonconvex fuel cost function of thermal units are considered. Among the methods, GA is the worst one since it obtains very high fuel cost, high constraint violation and long execution time. Hydro turbine with prohibited zone and

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nonconvex fuel cost function of thermal units are considered in the study [5]; however, the article only tested the performance of several modified versions of EP. The reported results have shown that several disadvantages of the EP such as poor solution quality and long computational time are not tackled yet.

Cuckoo search algorithm (CSA), a very efficient meta-heuristic algorithm, was developed by Yang and Deb in 2009 [11]. The CSA has been successfully and widely applied to several engineering fields, especially electrical engineering such as economic load dispatch [12], short-term fixed head hydrothermal scheduling [13], short-term cascaded hydrothermal scheduling [14]. The CSA was regarded as a few control parameter method with high successful rate and good solution quality since it has obtained better results in terms of fuel cost and execution time than other meta-heuristic such as GA, improved GA, PSO, DE as well as several recent new methods like artificial immune system and hybrid algorithms. Despite of the strong points, the CSA has just been pointed out by Walton *et al*. [15] that it also possesses several drawbacks including local solution search based on random walk and long execution time. Finally, the authors suggested a modified version of the CSA, called modified CSA (MCSA). The MCSA was built by improving the search ability of the CSA with several modifications. Namely, in the first new solution generation via Lévy flights all initial eggs are ranked and classified into two groups where top group consists of better eggs and abandoned group contains other eggs, and the updated step size associated with the Lévy flights is adaptive for the two groups at each iteration. The MCSA fast attracted intentions from researchers to deal with optimization problems such as Benchmark optimization functions [15], design process of integrated power systems for modern and energy self-sufficient farms [16] and short-term fixed hydrothermal scheduling [17].

In this paper, the modified Cuckoo Search Algorithm (MCSA) is first proposed for solving short-term cascaded hydrothermal scheduling problem considering cascaded hydropower plants. The effectiveness of the proposed MCSA methods has been tested on one system and the obtained results have been compared to those from methods reported in the paper.

2. Problem Formulation

In this section, the mathematical formulation of the short-term HTS problem consisting of N_1 thermal units and N_2 hydro units scheduled in M time sub-intervals with t_m hours for each is formulated. The objective of the problem is to minimize total cost of thermal units subject to the system and unit constraints.

The mathematical model of the problem is formulated as follows:

$$F = \sum_{m=1}^{M} \sum_{i=1}^{N_1} t_m \left(a_{si} + b_{si} P_{si,m} + c_{si} P_{si,m}^2 \right) \tag{1}$$

where a_{si}, b_{si}, c_{si} are fuel cost coefficients of thermal plant *i; $P_{si,m}$* is the power output of thermal plant i at subinterval *m.*
subject to:

2.1 Active Power Balance Constraint

$$\sum_{i=1}^{N_1} P_{si,m} + \sum_{j=1}^{N_2} P_{hj,m} - P_{L,m} - P_{D,m} = 0 \tag{2}$$

where $P_{L,m}$ and $P_{D,m}$ are load demand and transmission loss at subinterval *m*; $P_{hj,m}$ is the power output of hydro plant j at subinterval *m* and is determined by

$$P_{hj,m} = C_{1hj}(V_{j,m})^2 + C_{2hj}(Q_{j,m})^2 + C_{3hj}Q_{j,m}V_{j,m} + C_{4hj}V_{j,m} + C_{5hj}Q_{j,m} + C_{6hj} \tag{3}$$

where C_{1hj} , C_{2hj} , C_{3hj} , C_{4hj} , C_{5hj} , C_{6hj} are the coefficients of the jth hydropower plant

2.2 Hydraulic Continuity Constraint

$$V_{j,m-1} - V_{j,m} + I_{j,m} - Q_{j,m} - S_{j,m} + \sum_{i=1}^{Nu} \sum_{m=1}^{M} (Q_{i,m-\tau_{i,j}} + S_{i,m-\tau_{i,j}}) = 0 \quad (4)$$

where $V_{j,m}$, $I_{j,m}$ *and* $S_{j,m}$ are reservoir volume, water inflow and spillage discharge rate of *jth* hydropower plant in *mth* interval. $\tau_{i,j}$ is the water delay time between reservoir *j* and its up-stream *i* at interval *m* and Nu is the set of up-stream unitsdirectly above hydro-plant *j*.

2.3 Initial and Final Volume Constraints

$$V_{j,0} = V_{j,initial} \,;\, V_{j,M} = V_{j,End} \quad (5)$$

2.4 Upper and Lower Volume Constraints

$$V_{j,\min} \le V_{j,m} \le V_{j,\max} \,;\, j = 1,2,\ldots,N_2 \,;\, m = 1,2,\ldots,M \quad (6)$$

where $V_{j,max}$ and $V_{j,min}$ are the maximum and minimum reservoir storage of the hydro plant *j*, respectively.

2.5 Water Discharge Rate Limits

$$Q_{j,\min} \le Q_{j,m} \le Q_{j,\max} \,;\, j = 1,2,\ldots,N_2 \,;\, m = 1,2,\ldots,M \quad (7)$$

where $Q_{j,max}$ and $Q_{j,min}$ are the maximum and minimum water discharge of the hydro plant *j*.

2.6 Upper and Lower Generation Constraints

$$P_{si,\min} \le P_{si,m} \le P_{si,\max} \,;\, i = 1,2,\ldots,N_1 \,;\, m = 1,2,\ldots,M \quad (8)$$

$$P_{hj,\min} \le P_{hj,m} \le P_{hj,\max} \,;\, j = 1,2,\ldots,N_2 \,;\, m = 1,2,\ldots,M \quad (9)$$

where $P_{si,max}$, $P_{si,min}$ *and* $P_{hj,max}$, $P_{hj,min}$ are maximum, minimum power output of thermal plant *i* and hydro plant *j*, respectively.

3. Modified Cuckoo Search Algorithm for ST-CHTS Problems

3.1Modified Cuckoo Search Algorithm

The conventional CSA is comprised of three main parts including initialization, the first new solution generation via Lévy flights and the second new solution generation via the action of alien egg discovery. The initialization part is inspired from the laying and dumping egg of cuckoo birds in other species nests while the two new solution generations are inspired from final result of the cuckoo eggs after dumped in the host nest. As the host bird does not identify the alien egg, the egg will be hatched and carried over to the next generation. This phenomenon results in the first generation. Besides, there will be a fraction of the fixed number of eggs discovered as alien eggs and abandoned by the host bird. Obviously, a difference between the first and the second generations is that all the eggs from the initialization are newly generated in the first time via the Lévy flights while only a fraction of eggs is newly generated in the second time.

The new solutions generated via Lévy flights are obtained as below [14]:

$$X_i^{new} = X_i + \alpha.(X_{best} - X_i)\left(v \times \frac{\sigma_x(\beta)}{\sigma_y(\beta)}\right) \tag{10}$$

where X_{best} and X_i are the best egg and the *ith* egg among the number of eggs; $\alpha>0$ is an updated step size.

The value of α has a significant influence on the final solution because it will lead to different new solutions as it is set to different values. If this parameter is set to a high value, there is a huge difference between the old and new solutions and the optimal solution is either obtained fast or omitted. As the current iteration is high, the new obtained solution should be searched nearby the previous solution. However, the method has to find the optimal solution in a large search zone for this set value which may not reach the best optimal solution. Based on the analyzed drawback of the conventional CSA, it is clearly better to search for the optimal solution in a small zone as the iteration counter is increased to the maximum number of iterations which is predetermined for the iterative process [15].

The MCSA [15] has been focusing on the updated step size and improving the quality of all solutions generated via the Lévy flights. In the MCSA, all the eggs are ranked and classified into the top group with better quality eggs and the abandoned group with worse quality eggs before applying the first new solution generation via the Lévy flights. The abandoned group only focuses on the step size α which is decreased as the current iteration is increased. It is more complicated as generating new solution for the top group since it needs information exchanging between two eggs, one is randomly picked and the other is picked in order. Three cases may happen to the two picked eggs as follows: 1) the same egg is picked twice; 2) the two eggs have the same fitness function value; and 3) the randomly picked egg has lower or higher fitness value than the predetermined egg.

3.2 Units Calculation of Power Output for Slack Thermal Unit

In the MCSA most variables are first determined excluding slack ones, which are used to exactly meet power balance constraint (2) and hydraulic continuity constraint (4). The slack variables consisting of the water discharge of *jth* reservoir at subinterval M, $Q_{j,M,d}$ and power output of thermal unit 1 at subinterval m, $P_{s1,m}$ are obtained as follows [14]:

$$P_{s1,m} = P_{D,m} + P_{L,m} - \sum_{i=2}^{N_1} P_{si,m} - \sum_{j=1}^{N_2} P_{hj,m} \tag{11}$$

$$Q_{j,M,d} = V_{j,0} - V_{j,M} + \sum_{m=1}^{M} I_{j,m} - \sum_{m=1}^{M-1} Q_{j,m} - \sum_{m=1}^{M} S_{j,m} + \sum_{i=1}^{Nu}\sum_{m=1}^{M} (Q_{i,m-\tau_{i,j}} + S_{i,m-\tau_{i,j}}) = 0 \tag{12}$$

3.3 Implementation of the Modified Cuckoo Search Algorithm

3.3. 1 Initialization: Similar to other meta-heuristic algorithms, each nest of Np nests is represented by $X_d= [P_{si,m,d}\ Q_{j,m,d}]$ (d = 1, ..., N_p). Each nest X_d is randomly initialized where $P_{si,min} \le P_{si,m,d} \le P_{si,max}$ ($i=2, \ldots, N_1; m=1, \ldots, M$) and $Q_{j,min} \le Q_{j,m,d} \le Q_{j,max}$ ($j=1, \ldots, N_2; m=1, \ldots, M-1$).

Using (4), the reservoir volume at *mth* subinterval is obtained by

$$V_{j,m} = V_{j,m-1} + I_{j,m} - Q_{j,m} - S_{j,m} + \sum_{i=1}^{N_u} (Q_{j,m-\tau_{i,j}} + S_{i,m-\tau_{i,j}}) \tag{13}$$

The $Q_{j,M,d}$ is obtained by (12) and hydro generations can be then calculated using (3). The slack thermal unit is obtained using (11).

Based on the initial population of nests, the fitness function to be minimized corresponding to each nest for the considered problem is calculated.

$$FT_d = \begin{pmatrix} \sum_{m=1}^{M}\sum_{i=1}^{N1} F_i(P_{si,m,d}) + K_s \sum_{m=1}^{M}(P_{s1,m,d} - P_{s1}^{\lim})^2 + K_V \sum_{j=1}^{N2}\sum_{m=1}^{M-1}(V_{j,m,d} - V_j^{\lim})^2 \\ + K_Q \sum_{j=1}^{N2}\left((Q_{j,M,d} - Q_j^{\lim})^2\right) + K_h \sum_{j=1}^{N2}\sum_{m=1}^{M}(P_{hj,m,d} - P_{hj}^{\lim})^2 \end{pmatrix} \tag{14}$$

where K_s and K_h are respectively penalty factors for the slack thermal unit 1 and all hydro units; K_V and K_Q are respectively penalty factors for reservoir volume over *M-1* subintervals and water discharge at the subinterval M;

The limits of variables in (14) are obtained as below.

$$P_{s1}^{\lim} = \begin{cases} P_{s1,\max} & if\ P_{s1,m,d} > P_{s1,\max} \\ P_{s1,\min} & if\ P_{s1,m,d} < P_{s1,\min} \ ;m = 1,\dots,M \\ P_{s1,m,d} & \text{otherwise} \end{cases} \tag{15}$$

$$V_j^{\lim} = \begin{cases} V_{j,\max} & if\ V_{j,m,d} > V_{j,\max} \\ V_{j,\min} & if\ V_{j,m,d} < V_{j,\min} \ ;\ j = 1,..,N_2; \\ V_{j,m,d} & \text{otherwise} \qquad m = 1,..,M-1 \end{cases} \tag{16}$$

$$Q_j^{\lim} = \begin{cases} Q_{j,\max} & if\ Q_{j,M,d} > Q_{j,\max} \\ Q_{j,\min} & if\ Q_{j,M,d} < Q_{j,\min} \ ;\ j = 1,..,N_2 \\ Q_{j,M,d} & \text{otherwise} \end{cases} \tag{17}$$

$$P_{hj}^{\lim} = \begin{cases} P_{hj,\max} & if\ P_{hj,m,d} > P_{hj,\max} \\ P_{hj,\min} & if\ P_{hj,m,d} < P_{hj,\min} \ ;\ j = 1,..,N_2; \\ P_{hj,m,d} & \text{otherwise} \qquad m = 1,..,M \end{cases} \tag{18}$$

As described above, in the MCSA all nests are first sorted in the descending order of their fitness function value and then classified into two groups. The nests with high fitness function value $Xabandoned_d$ are put in the abandoned group and the other ones $Xtop_d$ are put in the top group. A nest which is randomly picked among the $Xtop_d$ nests is called $Xtop_r$ and another one with the best quality is named $Xbest_d$. The two new solution generations are respectively described as below.

3.3.1 Generation of New Solution via Lévy Distribution, Cauchy Distribution and Gaussian Distribution:

The first new solution generation via the Lévy flights

a) New solution generation for the abandoned group

Based on the modification applied to the abandoned eggs (d = $Notop$+1,..., N_p where *Notop and Np* are the number of eggs in the top group and in the initial population, respectively), the optimal path for the Lévy flights is calculated using Mantegna's algorithm as follows

$$Xabandoned_d^{new} = Xabandoned_d + \alpha \times rand_1 + \Delta X \tag{19}$$

where $rand_1$ is the distributed random number in [0, 1], the step size α is determined by $\frac{1}{\sqrt{G}}$ where G is the current iteration number, and ΔX is obtained by:

$$\Delta X = v \times \frac{\sigma_x(\beta)}{\sigma_y(\beta)} \times (Xabandoned_d - Xbest); \tag{20}$$

b) New solution generation for the top egg group

The modification is applied to the eggs in the top group (d = 1, …, *Notop*). The optimal path for the Lévy flights is calculated using Mantegna's algorithm as follows:

$$Xtop_d^{new} = Xtop_d + \alpha \times rand_2 \times \Delta X \tag{21}$$

where $rand_2$ is the distributed random numbers in [0, 1].

The value of α and ΔX will be determined depending on the considered cases as follows:

- *Case 1:* The same egg is picked twice

$$\Delta Xtop_d^{new} = v \times \frac{\sigma_x(\beta)}{\sigma_y(\beta)} \times (Xtop_d - Xbest) \tag{22}$$

where $\alpha = 1/G^2$.

- *Case 2*: Both eggs have the same fitness value function

$$\Delta Xtop_d^{new} = (Xtop_d - Xtop_r)/2 \tag{23}$$

where $\alpha = 1$.

- *Case 3:* The random egg has lower fitness than egg d

$$\Delta X_d^{new} = (Xtop_r - Xtop_d)/\varphi \tag{24}$$

or the random egg has higher fitness than egg d

$$\Delta X = (Xtop_d - Xtop_r)/\varphi \tag{25}$$

where $\alpha = 1$ *and* $\varphi = \left(1 + \sqrt{5}\right)/2$.

3.3.1.1 The Second New Solution Generation via Discovery of Alien Eggs: Similar to the conventional CSA, the second new solution generation via discovery of alien egg is also employed in the MCSA but all eggs of the top group and abandoned group are combined into one group first. The new solution due to this action can be found as follows:

$$X_d^{dis} = Xbest_d + K \times \Delta X_d^{dis} \tag{26}$$

where K is the updated coefficient determined based on the probability of a host bird to discover an alien egg in its nest [11] and ΔX_d^{dis} is the increased value [11].

The new solutions can violate their limits and need to be redefined by:

$$P_{si,m,d} = \begin{cases} P_{si,\max} & \text{if } P_{si,m,d} > P_{si,\max};\ i = 2,\dots,N_1 \\ P_{si,\min} & \text{if } P_{si,m,d} < P_{si,\min} \quad m = 1,\dots,M \\ P_{si,m,d} & \text{otherwise} \end{cases} \tag{27}$$

$$Q_{j,m,d} = \begin{cases} Q_{j,\max} & \text{if } Q_{j,m,d} > Q_{j,\max};\ j = 1,\dots,N_2 \\ Q_{j,\min} & \text{if } Q_{j,m,d} < Q_{j,\min} \quad m = 1,\dots,M-1 \\ Q_{j,m,d} & \text{otherwise} \end{cases} \tag{28}$$

The power output of N_2 hydro units and the slack thermal unit are then obtained, respectively. The fitness value is respectively calculated using equations (14). The nest corresponding to the best fitness function is then set to the best nest *Xbest*.

3.3.2 Stopping Criteria: The above algorithm is stopped when the maximum number of iterations is reached.

Overall Procedure

The overall procedure of the proposed MCSA for solving the ST- CHTS problem is described as follows.

Step 1: Select parameters including number of nests N_p, probability of alien eggs to to be abandoned P_a, the ratio of the number of eggs in top group to that in abandoned group and maximum number of iterations N_{max}.

Step 2: Initialize a population of N_p host nests as in Section 4.1 and calculate the slack unit 1 using eq. (11). Set the initial iteration counter G = 1.

Step 3: Evaluate the fitness function using (14) to evaluate and classify the eggs into two groups including abandoned group, $Xabandoned_d$ (d=$Notop$+1, …, Np) and top group, $XTop_d$ (d=1, …, $Notop$). The egg with the lowest fitness function value is set to *Gbest* in the population.

Step 4: Generate new solutions via Lévy flights for abandoned group as described in Section 4.2.1 and calculate the slack unit 1 using eq. (11).

Step 5: Generate new solutions via Lévy flights for top group as described in Section 4.2.2 and calculate the slack unit 1 using eq. (11).

Step 6: Put the new eggs in top group and abandoned group in the integrated group and evaluate all the eggs to determine the best egg with the lowest fitness function.

Step 7: Generate new solutions via the discovery of alien eggs as described in Section 4.3 and calculate the slack unit 1 using eq. (11).

Step 8: Evaluate the fitness function using (14) to determine the best egg, *Gbest*.

Step 9: If G < Gmax, G=G+1 and go back to step 3. Otherwise, terminate the iterative procedure.

4. Numerical Results

The proposed MCSA has been implemented for solving four hydrothermal systems classified into two cases, where case 1 considers two systems with four cascaded hydropower plants and one thermal plant with quadratic fuel cost function, and case 2 considers two systems with four cascaded hydropower plants and three thermal plants with nonconvex fuel cost function. All hydrothermal systems are scheduled in 24 one-hour subintervals. The proposed MCSA is coded in Matlab platform and run fifty independent trials on a 1.8 GHz PC with 4 GB of RAM.

Table 1. Results Obtained by MCSA

P_a	Min. total cost ($)	Aver. total cost ($)	Max. total cost ($)	Std. dev. ($)	Avg. CPU (s)
0.1	923538.7	923837.8	924115.4	136.2	230
0.2	923029.5	923465.4	923725.2	142.3	228
0.3	922927.5	923366.4	923655.5	166.0	243
0.4	923002.7	923290.8	923547.5	141.4	236
0.5	922831.4	923134.1	923615.4	175.0	233
0.6	922773.6	923141.9	923626.2	196.2	234
0.7	922788.4	923138.1	923560.8	171.8	237
0.8	922786.9	923153.8	923634.4	199.4	235
0.9	922839.5	923390.9	923946.4	252.5	232

4.1 Control Parameter Selection

The proposed MCSA consists of three conventional CSA parameters including the number of nests N_p, maximum number of iterations N_{max} and the probability of an alien egg to be discovered P_a and one individual parameter of the MCSA, the ratio of the number of eggs in top group to that in abandoned group. Among the parameters, the number of nests and the maximum number of iterations directly impact on the obtained results in terms of total generation cost and computational time. As the parameters are set to high values the better cost is obtained but the MCSA spends longer computational time terminating the search process, and vice versa. On the contrary, the probability of the eggs to be discovered does not influence the computational time but obtained generation cost. The optimal value of the parameter will be determined after setting to a range from 0.1 to 0.9 with a step of 0.1 and evaluating the minimum total generation cost obtained. Normally, the optimal value of the parameter falls in the two zones, [0.1, 0.5] and [0.5, 0.9] but the particular value is not fixed at one value. Besides, the ratio of the top nests to the abandoned nests also affect the solution quality. It has been suggested 1:3 in the studies [15, 17] and good results have been obtained. Therefore, the value is retained in the paper.

For implementation of the proposed MCSA, the number of nests and the maximum number of iterations are set to 100 and 15000 meanwhile the ratio of top nests to abandoned nests is 25:75 and the probability is set in range of 0.1 to 0.9 with a step of 0.1.

4.2 Obtained Results and Discussions

Case 1: *Two systems with quadratic fuel cost function of thermal units.*

This case considers two four-hydropower plant and one-thermal plant systems, where the data of system 1 and system 2 are respectively taken from [2] and [4]. The two systems have the same data of hydropower plants excluding transportation delay times and different fuel cost function of thermal unit.

The obtained results in terms of minimum total cost, maximum total cost, average total cost, standard deviation cost and average computational time for system 1 are given in Table 1. Clearly, the lowest value of minimum cost, average cost, maximum cost and standard deviation cost are obtained at Pa=0.6, 0.5, 0.4 and 0.1, respectively. As carefully observed from the minimum total cost column, the minimum total costs in range [0.6, 0.9] are less than those in range [0.1, 0.5] as mentioned in section selection of parameters.

Table 2. Obtained Result Comparison for System 1 of Case 1

Method	Min cost ($)	Average cost ($)	Max cost ($)	Avg. time (s)
GA[2]	942600	946609.1	951087	1920
BCGA [3]	926,922.71	-	-	-
RCGA [3]	925,940.03	-	-	-
CEP[5]	930166.25	930373.23	930927.01	2292.1
FEP[5]	930267.92	930897.44	931396.82	1911.2
IFEP[5]	930129.82	930290.13	930881.92	1033.2
GCPSO [6]	927288.4	936717.1	972658.3	182.4
GWPSO [6]	930622.5	940036.3	951253.2	129.1
LCPSO [6]	925618.5	926651.4	928219.8	103.5
LWPSO [6]	925383.8	926352.8	927240.1	82.9
EPSO [7]	922,904.00	-	-	-
DE [9]	923,991.08	-	-	-
MCSA	922773.6	923141.9	923626.2	234

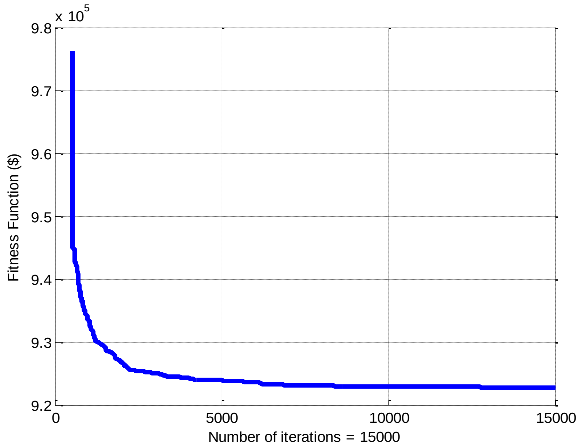

Figure 1. Convergence Characteristic for System 1 of Case 1

Table 3. Obtained Result Comparison for System 2 of Case 1

Method	Min cost ($)	Avg. time (s)
TPNN [9]	154808.5	-
ALM[9]	154739	-
PSO [18]	154705	-
ISAPSO[18]	154594 .7	-
MCSA	154594.4	231

Table 4. Optimal Solution Obtained for System 1 of Case 1

Hour	Water discharge (×10^4 m^3)				P_S (MW)
	plant 1	plant 2	plant 3	plant 4	
1	9.6262	6.5951	29.9542	13	1031.6022
2	9.6969	6.2608	29.9972	13.0007	1065.1271
3	8.9499	6.0978	28.2986	13.0029	1052.8443
4	8.4563	6.2135	29.9574	13	1000.7727
5	8.4734	6.0829	18.1989	13.0009	954.3588
6	8.1653	6.1552	17.5079	13	1052.2903
7	8.0089	6.4848	16.9502	13	1272.1805
8	8.607	7.4101	15.5737	13.0058	1591.4313
9	8.3575	7.5467	15.8458	13.0272	1827.1237
10	8.7161	7.5915	15.4544	13	1898.2346
11	8.6895	8.1715	15.2537	13.0571	1798.2119
12	8.5758	8.4514	15.5336	13	1874.8588
13	8.6059	8.6845	14.4437	13.3912	1782.4709
14	8.4309	8.6645	16.0137	15.5024	1734.5570
15	8.2826	8.7114	17.0762	14.8096	1671.9811
16	8.0756	9.0671	16.3803	15.5968	1601.5177
17	7.7806	9.1441	17.2503	15.2543	1669.6097
18	7.7112	9.4308	14.9736	15.6018	1670.1957
19	7.7541	10.4742	17.1273	16.6918	1762.5296
20	7.5693	10.9308	12.3502	16.8751	1793.9829
21	7.609	11.3778	10.0756	18.4505	1742.4466
22	7.3763	10.2376	10.203	19.6986	1624.0885
23	6.0615	10.6778	10.5695	20.5374	1360.5140
24	5.4202	11.5381	10.3758	22.4368	1106.7223

Table 2 reports the comparison of result for system 1 obtained by the proposed MCSA and other methods including Genetic algorithm in [2], Binary coded GA (BCGA) and real coded GA (RCGA) in [3], classical evolutionary programming (CEP), Fast EP (FEP) and improved Fast EP (IFEP) in [5], global constriction PSO (GCPSO), global weight factor PSO (GWPSO), Local constriction PSO (LCPSO) and local weight factor PSO (LWPSO) in [6], enhanced PSO (EPSO) in [7], and differential evolutionary (DE) in [9]. As observed from the table, the proposed method obtains better minimum cost, average cost and maximum cost than all methods available in the table. With respect to the computational time, the proposed method is faster than most methods excluding several versions of PSO in [6].

For system 2, The MCSA obtains the best minimum cost at Pa=0.4 and the comparison of the best cost among the MCSA and other methods such as two-phase neural network (TPNN) and augmented Lagrange method (ALM) in [4], PSO and improved self adaptive PSO (ISAPSO) in [18] indicated in Table 3. Obviously, the MCSA gets much better solution than all methods excluding ISAPSO. There is no simulation time reported for these methods in the table.

Consequently, the proposed is very efficient for determining the optimal solution for the ST-CHTS problem with quadratic fuel cost function of thermal units. The optimal solution obtained and cost convergence characteristic by the proposed method for system 1 of case 1 are given in Table 4 and Figure 1.

Case 2: *Two systems with nonconvex fuel cost function of thermal units.*

Two test systems with four cascaded hydropower plants and three thermal plants with nonconvex fuel cost function are considered in this case. The data for the two systems are shown in [19] and [20], respectively. The best minimum cost that the MCSA obtain for system 1 and 2 are respectively at Pa=0.4 and 0.7. Table 5 presents the cost and simulation time obtained from the MCSA and evolutionary programming based interactive fuzzy satisfying method (EP-IFS) in [19], Simulated annealing (SA), evolutionary programming (EP) and Particle swarm optimization (PSO) in [21], differential evolution (DE) and Real coded genetic algorithm (RCGA) [20]. As observed from the table, the proposed MCSA obtains much less cost than all methods for both system 1 and system 2. Furthermore, the MCSA is also much faster than DE and RCGA. The DE and RCGA were coded on a Pentium IV, 3GHz computer. Other methods have not reported computational time and computer. The optimal solution obtained by the proposed MCSA for test system 1 of the case is given in Table 6.

Table 5. Result Comparison for Case 2

Method	System 1		System 2	
	Cost ($)	time (s)	Cost ($)	time (s)
EP-IFS [19]	45063	-	-	-
SA [21]	47306	-	-	-
EP [21]	45466	-	-	-
PSO [21]	44740	-	-	-
DE [20]	-	-	110810	2554.1
RCGA [20]	-	-	112940	3156.5
MCSA	43476	265	82790	254

Table 6. Optimal Solution Obtained by MCSA for System 1 of Case 2

Hour	Q_1 (10^4 m^3)	Q_2 (10^4 m^3)	Q_3 (10^4 m^3)	Q_4 (10^4 m^3)	P_{s1} (MW)	P_{s2} (MW)	P_{s3} (MW)
1	11.0785	9.0216	20.8281	8.6901	166.9237	112.1210	105.5187
2	7.9614	11.4730	25.4217	12.9988	146.6096	207.7263	58.4384
3	8.1518	6.0656	17.4365	8.6723	143.7393	158.7603	82.1866
4	7.6695	6.4538	28.6583	6.4364	173.2124	118.4290	119.1982
5	5.6920	10.4340	29.9667	7.1448	174.3974	97.0926	148.2308
6	6.4772	6.2194	20.1650	6.4717	168.2794	253.6595	115.0933
7	7.0610	6.2239	14.2006	17.4276	174.2758	205.5627	158.3464
8	8.9154	7.0699	16.5039	10.0655	174.8861	288.8394	186.0087
9	11.1597	8.8520	14.1511	15.3448	174.0448	258.7376	200.9088
10	9.7363	7.4532	19.6945	16.2778	174.5498	265.2696	193.3469
11	9.4101	6.9752	18.9932	17.5401	174.1841	268.3244	198.8700
12	10.1721	8.1962	12.7667	19.7602	174.8303	298.6892	178.1246
13	7.2956	8.7684	19.3153	19.3260	132.6811	269.5498	241.7761
14	9.5292	7.8822	14.0598	12.8963	174.1711	265.2755	157.5033
15	6.7198	9.0522	18.6116	18.5624	170.3292	236.8770	135.2646
16	7.3888	11.8784	17.0181	18.8706	174.8517	247.3988	144.2679
17	7.7947	8.0547	11.7512	13.1900	174.6419	240.2377	203.6291
18	7.5930	6.8619	18.0923	18.7428	174.9501	291.2401	188.1574
19	10.9461	12.0948	21.6544	18.5888	174.7640	230.1911	176.1318
20	8.2280	9.2424	15.6426	18.7903	138.2875	274.4799	156.2832
21	5.0168	11.3892	16.1661	18.3426	153.1518	142.1125	156.3306
22	10.3895	7.8617	12.2974	19.9131	122.1920	200.5091	52.4855
23	5.4065	7.5649	12.5606	19.3712	174.1068	122.1877	106.5570
24	5.2070	6.9113	10.3930	18.3072	54.6683	182.6589	125.8985

5. Conclusions

In this paper, the proposed Modified Cuckoo Search Algorithm has been employed for determining the optimal solution for short-term hydrothermal system scheduling where cascaded hydropower plants and nonconvex objective are considered. The proposed MCSA has been tested on four systems and the results obtained are compared to those from several methods available in the paper. The comparison of generation fuel costs and computational time reveals that the MCSA is more effective and robust than these methods. Therefore, the proposed MCSA is one of the promising modern methods for solving the short-term cascaded hydrothermal scheduling problem where thermal units and a cascaded power plant system are connected.

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