An Effectively Enhanced Cuckoo Search Algorithm for Variable Head Short-Term Hydrothermal Scheduling

Thang Trung Nguyen, Anh Viet Truong, Dieu Ngoc Vo, Phu Trieu Ha and Loc Dac Ho

Abstract— *This paper proposes an effectively enhanced Cuckoo search algorithm (EECSA) for solving a variable head short-term hydrothermal scheduling (VH-STHTS) problem in which cascaded reservoirs and the complex objective considering valve point loading effects are taken into consideration. The EECSA is first developed in the study by improving the search ability of conventional Cuckoo search algorithm (CCSA) so as to speed up convergence and obtain high quality solutions. The EECSA is is tested on two hydrothermal systems in which the first system is composed of one thermal plant and four cascaded hydropower plants, and the second system consists of three thermal plant and four cascaded hydropower plants. The result comparisons between EECSA method and others reported in the paper indicates that EECSA is an efficient method with high quality solution and fast convergence speed.*

Keywords— **Enhanced Cuckoo Search Algorithm, variable head, short-term hydrothermal scheduling, valve point loading effects.**

1. INTRODUCTION

Variable head short-term hydrothermal scheduling (VH-STHTS) problem considers the water head of reservoirs as a variable during the scheduled period. In fact, due to a large difference between the inflow and the discharge, the volume of reservoir cannot be fixed at a value, leading to the variation of water head. The variable head short-term scheduling is more complex than the fixed head short-term scheduling because the hydro generation is a function with respect to water discharge and reservoir volume, which are varying during the optimal operation process [1].

Many algorithms have been successfully applied for dealing with the VH-STHTS problem so far such as decomposition and coordination techniques[2-3], evolutionary programming [4-5], genetic algorithm (GA) [6-8], two-phase neural network (TPNN) [9], differential evolution (DE) [10-12], Particle Swarm Optimization (PSO)[13-18], clonal selection algorithm [19], Hybrid differential evolution and sequential quadratic programming (HDE–SQP) algorithm [20], adaptive chaotic artificial bee colony (ACABC) algorithm [21], Teaching learning based optimization (TLBO) [22], Krill herd algorithm (KHA) [23], Symbiotic organisms search algorithm (SOSA) [24], Quasi-oppositional group search optimization (QOGSO) [25], Ant lion optimization (ALO) [26], Cuckoo search algorithm (CSA) [27] and modified Cuckoo search algorithm (MCSA) [28]. Among these methods, Decomposition and coordination techniques [2-3] are the two weakest methods for solving the problem and the obtained results have been acceptable for small system with simple constraints. In addition, the methods could not deal with problem taking valve point loading effects on thermal units.

In this paper, we proposes an effectively enhanced Cuckoo search algorithm by carrying out two modifications on Conventional Cuckoo search algorithm to improve the capability of CCSA. In the first modification, we focus on the second new solution generation via discovery of alien egg in aim to enable EECSA to avoid local optimum and converge to a global optimum faster. In the second modification, a new selection operation is applied to keep a population of dominant solutions in aim to enhance the global search ability for the next generation via Lévy flights. The proposed EECSA will be tested on two systems with different types of objective functions including quadratic function and nonconvex function. The obtained results from the proposed method compared to those from others reveals that the method is very efficient for the VH-STHTS problem.

2. PROBLEM FORMULATION

The task of VH-STHTS problem having N_1 thermal units and N_2 hydro units scheduled in M time sub-intervals is to determine optimal operation strategy so that the following objective can be obtained.

$$\text{Min } C_T = \sum_{m=1}^{M}\sum_{i=1}^{N_1} t_m F_{im} \tag{1}$$

where F_{im} is the fuel cost of the i^{th} thermal unit for one hour at the m^{th} subinterval and presented as follows:

$$F_{im} = \left[a_{si} + b_{si}P_{si,m} + c_s P_{si,m}^2 + \left| d_{si} \times \sin\left(e_{si} \times \left(P_{si}^{\min} - P_{si,m} \right) \right) \right| \right] \tag{2}$$

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In addition, a set of the following constraints must be exactly met.

- Load Demand Equality Constraint: The total power generated by thermal and hydro units must satisfy the load demand and power losses in transmission lines.

$$\sum_{i=1}^{N_1} P_{si,m} + \sum_{j=1}^{N_2} P_{hj,m} - P_{L,m} - P_{D,m} = 0 \qquad (3)$$

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 defined as the following function of water discharge and reservoir volume.

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

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

- Initial and Final Reservoir Storage

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

where $V_{j,0}$ and $V_{j,initial}$ are the initial volume of the reservoir j; $V_{j,M}$ and $V_{j,end}$ are the end volume of the reservoir j.

- Hydraulic Continuity Equation

$$V_{j,m-1} - V_{j,m} + I_{j,m} - Q_{j,m} - S_{j,m} + \sum_{i=1}^{Nu}\sum_{m=1}^{M}(Q_{i,m-\tau_{i,j}} + S_{i,m-\tau_{i,j}}) = 0 \qquad (6)$$

where $V_{j,m}$, $I_{j,m}$ *and* $S_{j,m}$ are reservoir volume, water inflow and spillage discharge rate of j^{th} hydropower plant in m^{th} 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 units directly above hydro-plant j.

- Reservoir Storage and water discharge limits

$$V_{j,\min} \le V_{j,m} \le V_{j,\max};\ j = 1, 2, ..., N_2; m = 1, 2, ..., M \qquad (7)$$

$$Q_{j,\min} \le Q_{j,m} \le Q_{j,\max};\ j = 1, 2, ..., N_2; m = 1, 2, ..., M \qquad (8)$$

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

- Generator Operating Limits

$$P_{si,\min} \le P_{si,m} \le P_{si,\max};\ i = 1, 2, ..., N_1; m = 1, 2, ..., M \qquad (9)$$

$$P_{hj,\min} \le P_{hj,m} \le P_{hj,\max};\ j = 1, 2, ..., N_2; m = 1, 2, ..., M \qquad (10)$$

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. EFFECTIVELY ENHANCED CUCKOO SEARCH ALGORITHM

The EECSA method is proposed by applying two modifications on CCSA including one modification on the second new solution generation via discovery of alien eggs and one modification on selection operation. The detail is described as follows.

3.1. The first modification on discovery of alien eggs

In the modification, there are two ways to produce new solutions via discovery of alien eggs as shown in eqs. (11) and (12) if random number is less than the probability of alien eggs to be abandoned

$$X_d^{new} = X_d + rand.(X_{randper1} - X_{ranper2})\ if\ D_d \ge tol \qquad (11)$$

$$X_d^{new} = X_d + rand.(X_{randper1} - X_{ranper2} + X_{randper3} - X_{ranper4})\ if\ D_d < tol \qquad (12)$$

Two new definitions shown in (11) and (12) are D_d and *tol* in which D_d is a ratio of two different fitness function values and obtained by (13) meanwhile *tol* is tolerance and selected one out of five values from 10^{-5} to 10^{-1}

$$D_d = \frac{Fitness_d - Fitness_{best}}{Fitness_{best}} \qquad (13)$$

In eq. (13), $Fitness_d$ and $Fitness_{best}$ are the values of fitness of solution d and the best solution among population.

3.2. The second modification on selection operation

The second modification is employed at the end of each iteration to keep N_p dominant solutions among N_p old solutions and N_p new solutions. In the new selection operation, all old solutions and all new solutions are integrated into one group with $2xN_p$ solutions. Then the solutions are evaluated and ranked to keep the first N_p dominant solutions with less fitness function than the *Np* remaining solutions.

4. IMPLEMENTATION OF EECSA METHOD

The EECSA for solving VH-STHTS problems is as follows:

4.1. Initialization

Similar to other meta-heuristic algorithms, each cuckoo nest in N_p nests is represented by a vector $X_d = [P_{si,m,d}\ ,\ Q_{j,m,d}]$ (d = 1, ..., N_p). Certainly, the upper and lower limits of each nest are respectively $X_{min}=[P_{simin},\ Q_{jmin}]$ and $X_{max}=[P_{simax},\ Q_{jmax}]$. Consequently, each nest X_d is randomly initialized within the limits $P_{si,min} \le P_{si,m,d} \le P_{si,max}$ ($i=2, …, N_1$; $m=1, …, M$) and $Q_{j,min} \le Q_{j,m,d} \le Q_{j,max}$ ($j=1, …., N_2$; $m=1, …., M-1$).

Using (6), the reservoir volume at subinterval m is obtained by:

$$V_{j,m} = V_{j,m-1} + I_{j,m} - Q_{j,m} - S_{j,m} + \sum_{i=1}^{N_u}(Q_{j,m-\tau_{i,j}} + S_{i,m-\tau_{i,j}}) \qquad (14)$$

The values of $Q_{j,M,d}$ is obtained by (15) and hydro generations can be then calculated using (5). Finally, the slack thermal unit 1 is obtained using (16).

$$Q_{j,M,d} = V_{j,0} - V_{j,M} + \sum_{m=1}^{M} I_{j,m} - \sum_{m=1}^{M-1} Q_{j,m} - \sum_{m=1}^{M} S_{j,m} + \sum_{i=1}^{Nu}\sum_{m=1}^{M}(Q_{i,m-\tau_{i,j}} + S_{i,m-\tau_{i,j}}) = 0 \qquad (15)$$

$$P_{s1,m} = P_{D,m} + P_{L,m} - \sum_{i=2}^{N_1} P_{si,m} - \sum_{j=1}^{N_2} P_{hj,m} \tag{16}$$

After all the variables of each egg has been obtained, the quality of each egg will be evaluated by calculating fitness function as follows.

$$FT_d = \left(\begin{array}{l} \sum_{m=1}^{M}\sum_{i=1}^{N1} F\left(P_{s,im}\right) + \phi_1 \sum_{m=1}^{M} (P_{s1,m,d} - P_{s1}^{\lim})^2 + \phi_2 \sum_{j=1}^{N2}\sum_{m=1}^{M-1} (V_{j,m,d} - V_j^{\lim})^2 \\ + \phi_3 \sum_{j=1}^{N2} \left((Q_{j,M,d} - Q_j^{\lim})^2 \right) + \phi_4 \sum_{j=1}^{N2}\sum_{m=1}^{M} (P_{hj,m,d} - P_{hj}^{\lim})^2 \end{array} \right) \tag{17}$$

where ϕ_1, ϕ_2, ϕ_3 and ϕ_4 are respectively penalty factors and the limits of variables are obtained by using their upper or lower limitations [27].

4.2. Reparation of new solutions

It cannot be sure that new solutions obtained Lévy flights and discovery of alien eggs can satisfy both upper and lower boundaries. Therefore, they should be checked and repaired as below.

$$X_d^{new} = \begin{cases} X_{d,\max} & \text{if} \quad X_d^{new} > X_{d,\max} \\ X_{d,\min} & \text{if} \quad X_d^{new} < X_{d,\min} \end{cases} \tag{18}$$

4.3. Stopping criteria

The termination criteria used to obtain the best solution is the maximum number of iterations. The process of computing will stop when the current iteration is equal to the maximum value.

5. NUMERICAL RESULTS

In this paper, the performance of EECSA is tested on two systems of the VH-ST-HTS where the first system neglects valve point loading effects on thermal units but the second consider the effects. The proposed methods is coded in Matlab platform and run one hundred independent trials for each value of P_a on a 2.0 GHz PC with 4 GB of RAM.

5.1 One test system with quadratic fuel cost function of thermal plants

In this section, one system with one thermal plant and four cascaded hydropower plants scheduled in 24 one-hour sub-intervals is considered [6]. For implementation of the proposed EECSA, the number of nests and the maximum number of iterations are respectively set to 200 and 2000 for each value of P_a ranging in [0.1, 0.9] with a step of 0.1. The best fuel cost obtained by EECSA at tol=10^{-4} and P_a = 0.5 is $ 922,366.84. The comparison of the obtained results by EECSA and other methods is reported in Table 1 for system 1. Clearly, EECSA can obtain better solution than all methods and converge faster than all methods because the fuel cost from proposed method is the lowest and its execution time is the shortest value. Consequently, it can be concluded that EECSA is every effective for system with quadratic fuel cost function of thermal units.

Table 1. Comparison of obtained results by EECSA and other methods for system 1

Method	Min cost($)	Avg. time (s)
CEP [5]	930166.25	2292.1
FEP [5]	930267.92	1911.2
IFEP [5]	930129.82	1033.2
GA [6]	926707	1920
BCGA [7]	926922.71	64.51
RCGA [7]	925940.03	57.52
MDE [10]	922555.44	NA
GCPSO [13]	927288.4	182.4
GWPSO [13]	930622.5	129.1
LCPSO [13]	925618.5	103.5
LWPSO [13]	925383.8	82.9
EGA [15]	934727.00	NA
PSO [15]	928878.00	NA
EPSO [15]	922904.00	NA
IPSO[16]	922553.49	NA
CSA-Lévy [27]	927934.23	79.08
CSACauchy [27]	927967.66	81.30
CSA-Gauss [27]	927957.26	85.75
MCSA [28]	922773.6	234
EECSA	922366.84	24.6

5.2 One test system with nonconvex fuel cost function of thermal plants

In this section, one system with nonconvex fuel cost function is employed to verify the efficiency of the proposed method. The system is composed of four cascaded hydropower plants and three thermal plants. The optimization period is 24 one-hour subintervals. The data of the system 2 is taken from [33]. The population and the maximum iterations are respectively set to 200 and 6,000 for implementing EECSA. The best fuel cost obtained by EECSA at tol=10^{-4} and P_a = 0.6 is $ 41,661.8193. The comparisons of obtained results in terms of fuel cost and execution time are reported in Table 2. Clearly, EECSA is the best method with the lowest fuel cost and the fastest execution time. Consequently, it can be concluded that EECSA is a very promising method for solving the VH-STHTS problem with nonconvex fuel cost function of thermal units.

Table 2. Comparison of obtained results by EECSA and other methods for system 2

Method	Cost ($)	CPU (s)
SA [14]	47,306.00	NA
EP [14]	45,466.00	NA
PSO [14]	44,740.00	NA
DE [11]	44,526.10	200
MDE [11]	42,611.14	125
HDE [11]	42,337.30	48
MHDE [11]	41,856.50	31
Clonal selection[19]	42440.574	109
KHA [23]	41926.00	NA
QOGSO [25]	42120.02	625.07
MCSA [28]	43476	254
EECSA	41064.897	75.3

6. CONCLUSIONS

The paper presents the application of an effectively enhanced Cuckoo search algorithm for solving optimal short-term hydrothermal generation cooperation problem taking variable head of hydropower plant into consideration. In order to verify the powerful search of the proposed EECSA, two systems including quadratic fuel cost function and nonconvex fuel cost function of thermal units are employed. The analysis on the comparison has revealed that the proposed method is very efficient for solving the optimal short-term hydrothermal scheduling problem.

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