

Optimal power generation for wind-hydro-thermal system using meta-heuristic algorithms

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ABSTRACT

In this paper, cuckoo search algorithm (CSA) is suggested for determining optimal operation parameters of the combined wind turbine and hydrothermal system (CWHTS) in order to minimize total fuel cost of all operating thermal power plants while all constraints of plants and system are exactly satisfied. In addition to CSA, Particle swarm optimization (PSO), PSO with constriction factor and inertia weight factor (FCIW-PSO) and social ski-driver (SSD) are also implemented for comparisons. The CWHTS is optimally scheduled over twenty-four one-hour interval and total cost of producing power energy is employed for comparison. Via numerical results and graphical results, it indicates CSA can reach much better results than other ones in terms of lower total cost, higher success rate and faster search process. Consequently, the conclusion is confirmed that CSA is a very efficient method for the problem of determining optimal operation parameters of CWHTS.

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NOMENCLATURE

N_{tp}	Number of thermal units
N_{in}	Number of scheduled intervals
k_i, m_i, n_i	Coefficient of fuel cost function
$PT_{i,j}, PH_{k,j}, PW_{w,j}$	Generation of the i th thermal unit, the k th hydro unit and the w th wind turbine at the j th interval
$N_{tp}, N_{hp}, N_{wt}, N_{in}$	Number of thermal units, hydro units, wind turbines and intervals.
$P_{load,j}, P_{loss,j}$	Power of load and loss at the j th interval
$PW_w, PW_{w,rate}$	Generation and rated generation of the w th wind turbine
$WV, WV_{rate}, WV_{cut-in}, WV_{cut-out}$	Wind speed, rated wind speed, cut-in speed and cut-out speed
$PW_{w,min}, PW_{w,max}$	Minimum and maximum generation of the w th wind turbine
X_k, Y_k, Z_k	Coefficients of the k th hydro unit's generation
$Q_{k,min}, Q_{k,max}$	Minimum and maximum discharge of the k th hydro unit
$Q_{k,j}$	Discharge of the k th hydro unit at the j th interval
$W_{avai,k}$	available water for power generation over the scheduled intervals

$PH_{k,min}, PH_{k,max}$	Minimum and maximum power generation of the k th hydro unit
Sol_x, Sol_x^{new}	The x th current solution and new solution
Fit_x, Fit_x^{new}	Fitness function the the x th current and new solution

1. INTRODUCTION

Hydrothermal system scheduling (HTSS) problem is a very important problem in optimization operation of power systems where hydropower plants and thermal plants are accounting for a high rate of all power sources in exiting power systems [1]. In general, hydropower plants use water in river to drive turbines and run generators for producing electricity to loads while thermal power plants must employ fossil fuel such as gas, oil and coal to drive gas turbines or steam turbines for generating electricity. Water can be exhausted and full in rivers dependent on weather, namely rain and sun in seasons [2]. On the contrary, fossil fuels cannot be recovered after using. As a result, cost of generating electricity or price of fossil fuels in thermal power plants is a significant issue but cost of water in hydropower plants is normally ignored. Main issues regarding hydropower plants are hydraulic constraints such as discharge limit, spillage, flood, and reservoir limits. So, in hydropower system scheduling problem, the most difficulty issue is to solve the hydraulic constraints successfully while the main target is to reduce cost of generating electricity in thermal power plants [3].

Basically, hydrothermal system scheduling problem can be divided into short-term [1-10], medium-term [11-15] and long-term models [16-20] based on the time period of scheduled optimization. Short-term HTSS problem is classified into fixed-head model [1-7] and variable head model [8-10], and this problem was also the most attracted problem among three different time period types. The main difference of the problems is scheduled time period. Short-term HTSS problem considers one day to one week while long-term HTSS considers over one year with twelve months or four seasons. The time from one week to one month or from one month to one season is taken into account in medium-term HTSS problem. The three problems have the same characteristic that is to consider cost of producing electricity in thermal power plants as an objective and neglect cost in hydropower plants. In addition, renewable energies like solar energy and wind energy are not considered in the problem.

In recent years, wind turbines have been considered in conventional power systems with hydrothermal plants. The optimal generation between these thermal plants and these wind turbines was successfully solved by using metaheuristic algorithms like bee colony algorithm (BCA) [21] and Wait-See algorithm (WSA) [22]. Then, the integrated system was expanded by adding hydropower plants and the optimal generation of the wind-hydro-thermal system were solved by using nondominated sorting genetic algorithm-III (NSGA-III) [23], multi-objective bee colony optimization algorithm (MOBCOA) [24], two-stage stochastic method (TSSM) [25] and sine-cosine algorithm (SCA) [26]. In [23], multi objective functions including fuel cost and power loss are considered in which power generation of wind farms is considered as a control variable of the combined system. In [24], uncertainty of wind speed was considered by considering Weibull distribution function. In the study, wind turbines are calculated three cost, direction cost, reserve cost and penalty cost. In [25-26], cascaded hydropower plants are considered together with the power generation of thermal power plants and wind turbines. Similar to [24], the two studies also considered the Weibull function and three costs of wind turbines. In general, almost all studies applied metaheuristics and mainly focused on the highly successful constraint handling ability of rather than reaching the best solutions for the problem. In addition, power loss of the system due to the impact of resistance and reactance of conductors was not considered in these studies. This is also understood because these studies were first application of methods for solving the new problem.

In this paper, short-term HTSS problem with fixed-head model is expanded by adding wind turbines and considering operation range of them. On the contrary to other studies, all constraints of hydropower plants are taken into account including discharge limit, available water and generator limits. Thermal power plants are not constrained by available fossil fuel quantity but generators. Wind turbines are constrained by capacity and operation wind speeds. The main purpose is to calculate cost of thermal power plants and determine the most optimal generation for reducing this cost. For reaching the optimal solutions of the problem, we apply PSO (PSO) [27], CFIWPSO [28], SSD [29] and CSA [30].

In summary, the contributions of the paper are follows:

- Develop wind-hydrothermal system scheduling problem with short-term model
- Propose the best decision variable selection method
- Investigate performance of PSO, FCIW-PSO, SSD and CSA

2. FORMULATION OF OPTIMAL SCHEDULING OF WIND-HYDRO-THERMAL SYSTEM

In the section, a wind-hydrothermal system with fixed head model is in detail described by using figure and formulas. Figure 1 shows a system with one thermal power plant, one hydropower plant and one wind farm located at load. The objective and constraints as well as assumption of the problem are as follows:

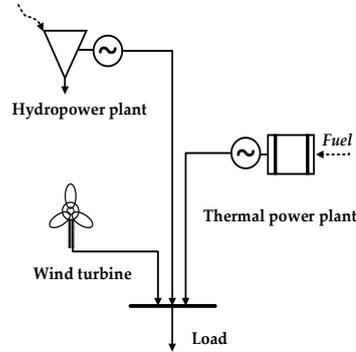


Figure 1. A typical wind-hydro-thermal system

2.1. Objective function

Total fuel cost (TFC) for generating electricity from all thermal power plants is considered as a major part that needs to be minimized as much as possible. The objective is shown as follows:

$$\text{Minimize } TFC = \sum_{i=1}^{N_{tp}} \sum_{j=1}^{N_{in}} (k_i + m_i PT_{i,j} + n_i (PT_{i,j})^2) \quad (1)$$

In (1), we only focus on the reduction of fuel cost from thermal power plants meanwhile the electric generation cost from hydropower plants and wind power plants is neglected. The assumption of neglecting the electric cost from hydroelectric plant is taken from the idea that water is a nature source with very low price whereas all power energy from wind power plants is absolutely used with the same price and the same cost over one scheduled day.

2.2. The set of constraints

a. Constraints from power system

In power systems, the balance between the generated and consumed power must be guaranteed as the following model:

$$\sum_{i=1}^{N_{tp}} PT_{i,j} + \sum_{k=1}^{N_{hp}} PH_{k,j} + \sum_{w=1}^{N_{wt}} PW_{w,j} - P_{Load,j} - P_{Loss,j} = 0 \quad (2)$$

b. Constraint from thermal plants

Power generation of thermal power plants is limited as follows:

$$PT_{i,min} \leq PT_{i,j} \leq PT_{i,max} \quad (3)$$

c. Constraint from wind turbines

Basically, power generation of a wind turbine is much dependent on wind speed. The range of generation can be seen by the following equation [25]:

$$PW_w = \begin{cases} 0, & (WV < WV_{cut-in} \text{ and } WV > WV_{cut-out}) \\ PW_{w,rate} \times \frac{(WV - WV_{cut-in})}{(WV_{rate} - WV_{cut-in})}, & (WV_{cut-in} \leq WV \leq WV_{rate}) \\ PW_{w,rate}, & (WV_{rate} \leq WV \leq WV_{cut-out}) \end{cases} \quad (4)$$

So, wind turbines are also constrained by power generation as follows:

$$PW_{w,min} \leq PW_{w,j} \leq PW_{w,max} \quad (5)$$

d. Constraints from hydropower plants:

Limits of water Discharge: Water that is discharged through a turbine must be in a predetermined range as follows:

$$Q_{k,min} \leq Q_{k,j} \leq Q_{k,max} \quad (6)$$

where $Q_{k,j}$ is determined as follows:

$$Q_{k,j} = X_k + Y_k PH_{k,j} + Z_k (PH_{k,j})^2 \quad (7)$$

In addition, the total water discharge over N_{in} intervals must be equal to available as the constraint below:

$$\sum_{j=1}^{N_{in}} Q_{k,j} = W_{avai,k} \quad (8)$$

e. Constraint of generators: Hydro generation is constrained by.

$$PH_{k,min} \leq PH_{k,j} \leq PH_{k,max} \quad (9)$$

3. CUCKOO SEARCH ALGORITHM

3.1. New solution generation mechanism

On the contrary to PSO and SSD, CSA performs two mechanisms to produce new solutions. For each mechanism, the whole population is newly updated. So, total new solutions generated by CSA is two times that of PSO and SSD. Lévy flights is applied in the first mechanism while mutation operation is employed in the second one. The two mechanisms are mathematically formulated as follows:

$$Sol_x^{new} = Sol_x + \alpha_0 (Sol_x - Sol_{Best}) \otimes L(\beta) \quad (10)$$

$$Sol_x^{new} = \begin{cases} Sol_x + rd_1 (Sol_1 - Sol_2) & \text{if } rd_2 < Pro \\ Sol_x & \text{otherwise} \end{cases} \quad (11)$$

where α_0 is a positive scaling factor; $L(\beta)$ is Lévy distribution function [10]; and Sol_{Best} is the so-far best solution among the current population; rd_1 and rd_2 are random numbers in the range between 0 and 1; Pro is old solution replacement probability, which is selected within 0 and 1. Sol_1 and Sol_2 are two randomly selected solutions.

3.2. Promising solution selection mechanism

This mechanism is applied to performance comparison of quality between the new xth solution and the old xth solution to retain a better solution and abandon a worse one. So, fitness function must be calculated for each old and new solution. Then, the following model is applied.

$$Sol_x = \begin{cases} Sol_x & \text{if } Fit_x < Fit_x^{new} \\ Sol_x^{new} & \text{Otherwise} \end{cases} \quad (12)$$

4. RESULTS NUMERICAL RESULTS

In this section, the effectiveness of CSA is compared to that of PSO, CFIW-PSO and SSD on the system with one thermal power plant, one hydropower plant and one wind power plant. The system is scheduled over twenty-four one-hour intervals. The hydrothermal systems and loss coefficients are taken

from Table A1 in page 284 [10] while the wind farm data is taken from wind farm 1 in Table 6 in page 760 [31]. The whole data and loss coefficients are shown in Table A1, Table A2 and Table A3 in Appendix. The four methods are coded on Matlab program language and a computer with CPU of Intel Core i7-2.4GHz-RAM 4GB for obtaining 50 successful runs.

In order to run these methods, population size (*PS*) and the maximum iteration (*MI*) are set to 20 and 2000 for CSA, 40 and 2000 for PSO, CFIW-PSO and SSD. The results from 50 successful runs are summarized in Table 1 in addition to saving cost and improvement shown in Figures 2 and 3. In the two figures, saving cost and the corresponding improvement level of CSA as compared to PSO, CFIW-PSO and SSD are shown. So, there is no bar to show the result of CSA in the two figures. From the figures, it can indicate that as compared to other methods CSA can reach very high reduction of minimum cost with \$6029.58, mean cost with \$7576.37 and maximum cost with \$9305.77 the reduction cost of CSA is corresponding to the improvement level of 8%, 0.94% and 2.1% over PSO, CFIW-PSO and SSD. Similarly, the mean cost and the highest cost of CSA are also much less than other methods. The improvement level of mean cost and the highest cost can be up to 4% and 9.8%.

Table 1. Summary of results

	PSO	CFIW-PSO	SSD	CSA
Minimum cost (\$)	75789.64	70420.13	71236.93	69760.06
Average cost (\$)	77362.83	72718.63	73327.8	69786.46
Maximum cost (\$)	79306.06	75847.33	77212.04	70000.29
Standard deviation (\$)	729.5481	1438.077	1366.289	41.4461
Success rate (%)	848/50	86/50	107/50	50/50

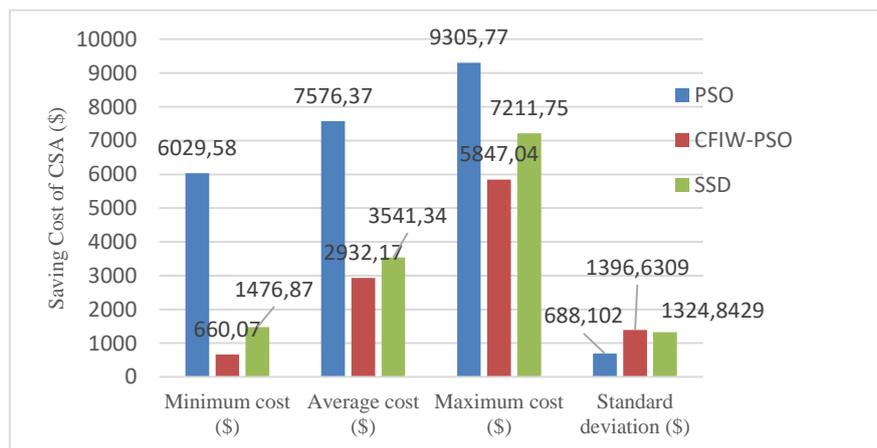


Figure 2. Saving cost of CSA as compared to PSO, CFIW-PSO and SSD

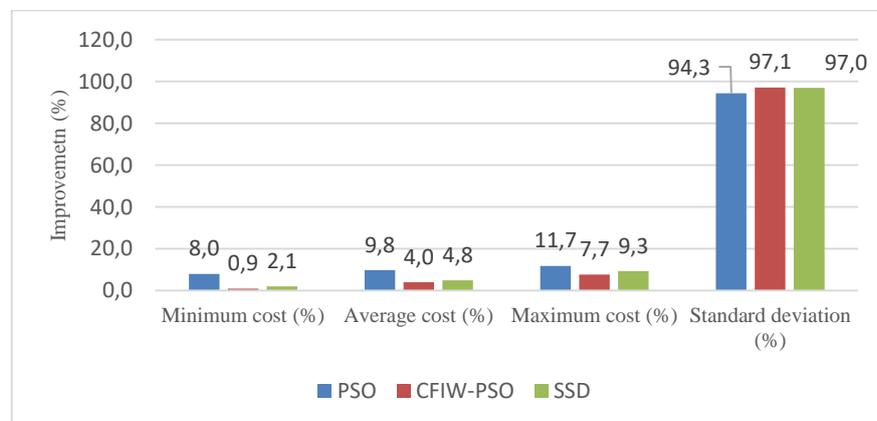


Figure 3. Improvement of CSA over PSO, CFIW-PSO and SSD

In addition, the best run, the mean run, the worst run and the cost of 50 runs can be observed from Figures 4-7. The figures indicate that CSA is always the best method with the fastest speed and all better runs. Consequently, it leads to a conclusion that CSA is the best method for the first system. Optimal power generation obtained by CSA is shown in Figure 8.

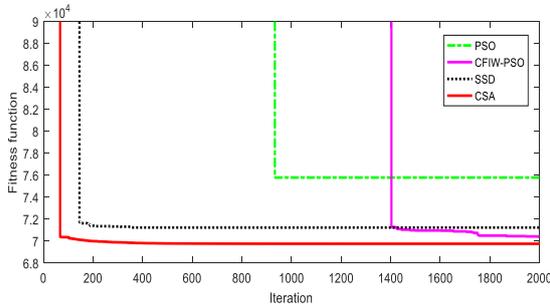


Figure 4. The best convergence characteristic of four applied methods

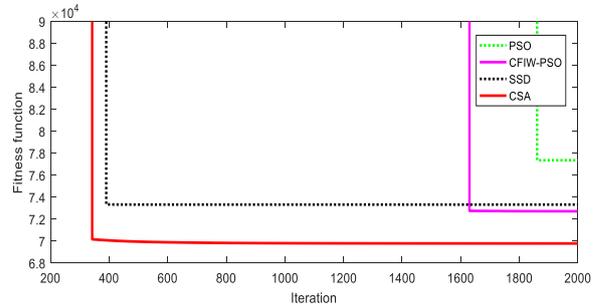


Figure 5. The mean convergence characteristic over 50 successful runs of four applied methods

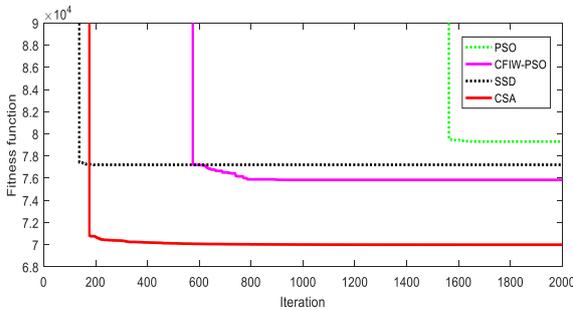


Figure 6. The worst convergence characteristic of four applied methods

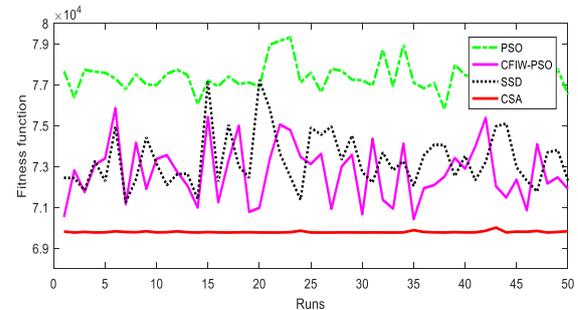


Figure 7. Fuel cost of 50 successful runs obtained by four applied methods

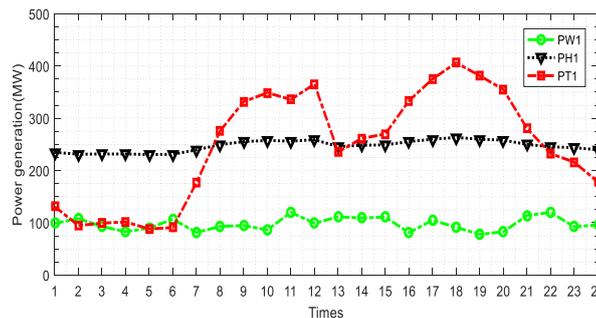


Figure 8. Optimal power generation obtained by CSA

5. CONCLUSION

In this paper, four applied methods including CSA, PSO, FCIW-PSO and SSD have been applied for solving combined wind turbine and hydrothermal systems. The four methods have been implemented for reaching 50 successful runs for comparisons. Numerical results including the best cost, mean cost and maximum cost in addition to graphical results including convergence characteristics have been analyzed for evaluating performance of these methods. CSA was superior to three other ones in finding the best solution, reach very high success rate and faster speed. So, it can be concluded that CSA is a very efficient method for determining optimal parameters of combined wind turbines and hydrothermal systems.

APPENDIX

Table A1. Data of thermal power plant

k_l	m_l	n_l	$PT_{l,min}$ (MW)	$PT_{l,max}$ (MW)
373.7	9.606	0.001991	0	505

Table A2. Data of hydroelectric plant

X_l	Y_l	Z_l	$W_{avail,l}$	$PH_{l,min}$ (MW)	$PH_{l,max}$ (MW)
61.53	-0.009079	0.0007749	2559.6	0	300

The loss coefficient matrix of the system

$$B = \begin{bmatrix} 0.00005 & 0.00001 \\ 0.00001 & 0.00015 \end{bmatrix}$$

Table A3. Load and wind power over 24 one-hour intervals

j	$P_{Load,j}$	$PW_{1,j}$	j	$P_{Load,j}$	$PW_{1,j}$	j	$P_{Load,j}$	$PW_{1,j}$
1	455	99	9	665	94.8	17	721	105
2	425	108	10	675	86.4	18	740	91.2
3	415	93	11	695	120	19	700	78
4	407	82.8	12	705	99	20	678	82.8
5	400	90	13	580	111.6	21	630	114
6	420	106.8	14	605	109.2	22	585	120
7	487	81.6	15	616	111	23	540	92.4
8	604	93	16	653	81	24	503	96

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