International Journal of Electrical and Computer Engineering (IJECE)
Vol. 9, No. 5, October 2019, pp. 3359~3365
ISSN: 2088-8708, DOI: 10.11591/ijece.v9i5.pp3359-3365

Short-term optimal hydro-thermal scheduling using clustered adaptive teaching learning based optimization

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Article Info

Article history:

Received Dec 23, 2018
Revised Apr 3, 2019
Accepted Apr 11, 2019

Keywords:

Evolutionary algorithms
Generation scheduling
Hydro-thermal scheduling
Multi-chain reservoirs

ABSTRACT

In this paper, Clustered Adaptive Teaching Learning Based Optimization (CATLBO) algorithm is proposed for determining the optimal hourly schedule of power generation in a hydro-thermal power system. In the proposed approach, a multi-reservoir cascaded hydro-electric system with a non-linear relationship between water discharge rate, net head and power generation is considered. Constraints such as power balance, water balance, reservoir volume limits and operation limits of hydro and thermal plants are considered. The feasibility and effectiveness of the proposed algorithm is demonstrated through a test system, and the results are compared with existing conventional and evolutionary algorithms. Simulation results reveals that the proposed CATLBO algorithm appears to be the best in terms of convergence speed and optimal cost compared with other techniques.

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1. INTRODUCTION

Hydro power plants are multi-purpose projects, which are not only generate the electrical power but also responsible for the fulfillment of irrigation requirements of nearby zone [1]. Short term hydro-thermal scheduling (ST-HTS) determines the optimal power generation of the hydro and thermal generators, so as to minimize the total cost of thermal generators, while satisfying the constraints of hydro-thermal power system. This is one of the constrained power system optimization problem, which has complex, non-linear characteristics with various types of constraints including power balance, water balance, physical limitations on the reservoir and turbine flow rate, water transport delay between connected reservoirs, and loading limits of both hydro and thermal plants [2]. In general, the objective in the hydro-thermal scheduling problem is to minimize the total fuel cost of thermal generating units. In the literature, various classical methods are developed for solving this problem. However, these methods have difficulties in handling constraints like non-convex and prohibited operating regions.

Background: In recent years, meta-heuristic optimization algorithms have been extensively used because to their feasibility, versatility and robustness in reaching the global optimal solution. These include Genetic Algorithms (GA) [3], Evolutionary Programming (EP) [4], Particle Swarm Optimization (PSO) [5], Improved PSO [6], Simulated Annealing (SA) [7], Evolutionary Strategy (ES) [8], etc. Reference [9] proposes a Modified Seeker Optimization Algorithm (MSOA) for solving the Short-Term Hydro Thermal Scheduling (ST-HTS) problem considering operational constraints. In [10], a Modified Differential Evolution (MDE) algorithm is developed for solving ST-HTS problem. A two-phase neural network based optimization algorithm for ST-HTS problem is proposed in [11]. In [12], an efficient optimization procedure based on the clonal selection algorithm (CSA) is proposed for the solution of ST-HTS problem. In [13], Benders Decomposition method improved by Bacterial Foraging oriented by Particle Swarm Optimization method

(BDI-BFPSO) is used for solving AC constrained hydro-thermal generation scheduling problem. In [14], genetic algorithm is applied to solve the hydro-thermal scheduling (HTS) problem with optimal power flow (OPF). The hydro sub-problem is solved using genetic algorithm, and the thermal sub-problem is solved using lambda iteration technique without line losses. Reference [15] presents a clonal real-coded quantum-inspired evolutionary algorithm (CRQEA) with Cauchy mutation for solving ST-HTS problem. In this algorithm, real-coded rule is adopted for handling continuous variables.

The Problem: Reference [16] develops a ST-HTS formulation, which takes into consideration of scheduling the thermal units as well as the hydro and thermal generations in a scheduling horizon consisting of a number of intervals. In [17], PSO is applied to determine the optimal hourly schedule of power generation in a hydro-thermal power system. Reference [18] develops a model for dealing with the ST-HTS problem, incorporating, as a whole, three problems traditionally analyzed separately: short-term hydro thermal scheduling (HTS), unit-commitment, and economic dispatch. An enhanced differential evolution (EDE) algorithm to solve HTS problem using chaos theory to obtain self-adaptive parameter settings in differential evolution (DE) is proposed in [19]. A cultural algorithm to solve the optimal daily generation scheduling of hydro-thermal power systems, which takes the water transport delay time between connected reservoirs into consideration, and can conveniently deal with the complicated hydraulic coupling simultaneously, is proposed in [20].

The Proposed Solution: In recent years, optimization method known as Teaching Learning Based Optimization (TLBO) has becoming more popular, and has been used in many practical cases, mainly because it has demonstrated good robust, convergence properties, and is principally easy to understand. TLBO is a recently developed evolutionary algorithm based on two basic concepts of education, namely teaching phase and learning phase [21]. In first phase, learners improve their knowledge or ability through the teaching methodology of teacher, and in second part learners increase their knowledge by interactions among themselves. The algorithm does not require any algorithm specific parameters which makes the algorithm robust. In [22], teaching learning based optimization (TLBO) to solve ST-HTS problem considering non-linearities like valve point loading effects of the thermal unit and prohibited discharge zone of water reservoir of the hydro plants is proposed. An approach for solving short-term HTS using an integrated algorithm based on teaching learning based optimization (TLBO) and oppositional based learning (OBL) is proposed in [23].

In this paper, Clustered Adaptive Teaching Learning Based Optimization (CATLBO) algorithm is proposed to solve the short-term HTS problem. The proposed algorithm is applied to solve the daily generation scheduling of a test hydro system with four interconnected cascade hydro plants. Simulation results demonstrate the effectiveness, feasibility and validity of the proposed method in terms of solution precision, when compared with all other algorithms in the literature.

The rest of the paper is organized as follows: Section 2 presents the problem formulation for short term hydro thermal scheduling (ST-HTS). Section 3 presents the results and discussion. Finally, Section 4 summarizes the contributions with concluding remarks.

2. SHORT TERM HYDRO-THERMAL SCHEDULING (ST-HTS): PROBLEM FORMULATION

The ST-HTS problem aims at allocating the water discharge among shorter time intervals in order to minimize the fuel cost of thermal generators during the scheduling interval, while satisfying various equality and inequality constraints.

2.1. Mathematical formulation for ST-HTS

The ST-HTS problem is aimed to minimize the total thermal power generation cost, while making use of the availability of hydro resource as much as possible. The objective function for ST-HTS problem is formulated as [24], minimize, total production cost (F), i.e.,

$$F = \sum_{t=1}^{T} \sum_{i=1}^{M} C_{it}(P_{it}^{T}) \tag{1}$$

where t is the index for time interval, T is the total number of time intervals for scheduling period, M is the total number of thermal plants, P_{it} is the thermal power generation of ith thermal plant during time t, $C_{it}(P_{it})$ is the production cost for generating the power P_{it}. In general, the fuel cost of thermal generators can be expressed as a quadratic function of power generation [25], and is given by,

$$C_{it}(P_{it}^{T}) = a_i + b_i P_{it}^{T} + c_i (P_{it}^{T})^2 \tag{2}$$

where a_i, b_i and c_i are the fuel cost coefficients of ith thermal power plant.

2.2. Equality Constraints for the ST-HTS Problem
2.2.1. System power balance constraints

The total power generation from hydro and thermal units/ plants is the sum of total system load/ demand plus system losses in each hour of the scheduling interval [26].

$$P_{it} + \sum_{j=1}^{N} PH_{jt} = P_{Dt} + P_{loss,t} \qquad t = 1,2,\dots,T \tag{3}$$

where N is the total number of hydro plants, P_{Dt} is the system load/demand during time period t, and $P_{loss,t}$ is the transmission losses of the system during time period t. The hydro power generation (PH_{jt}) is expressed as a function of water discharge rate and storage volume as [24],

$$PH_{jt} = c_{1j}V_{jt}^2 + c_{2j}q_{jt}^2 + c_{3j}(V_{jt}q_{jt}) + c_{4j}V_{jt} + c_{5j}q_{jt} + c_{6j} \tag{4}$$

Here, c_{1j}, c_{2j}, c_{3j}, c_{4j}, c_{5j} and c_{6j} are the power generation coefficients of jth hydro plant.

2.2.2. Water dynamic balance (or) hydraulic continuity constraint

The storage reservoir volume limits are expressed with given initial and final volumes as follows:

$$V_{jt} = V_{j,t-1} + \sum_{m=1}^{\varphi_j}(q_{m,t-\tau} + Spl_{m,t-\tau}) + I_{jt} - q_{jt} - Spl_{jt} \qquad m\epsilon\varphi_j \tag{5}$$

where φ_j is the set of upstream units directly above the hydro-plant, τ is the water delay time between reservoir and its upstream. I_{jt} is the natural inflow into reservoir j at time interval t, q_{jt} is the water discharge of hydro plant j at time interval t, Spl_{jt} is the water spillage of hydro plant j at time interval t, and V_{jt} is the water volume of reservoir j at the end of time interval t.

2.3. Inequality Constraints for ST-HTS Problem
2.3.1. Thermal generators power limits

The generation limits of equivalent thermal generator is given by [27],

$$P_i^{min} \le P_{it} \le P_i^{max} \tag{6}$$

where P_i^{min} and P_i^{max} are minimum and maximum power generation of ith thermal power plant [28].

2.3.2. Hydro generators power limits

The operating limit of hydro plant is given by [24],

$$PH_j^{min} \le PH_{jt} \le PH_j^{max} \tag{7}$$

where PH_j^{min} and PH_j^{max} are the minimum and maximum power generation of hydro plant j.

2.3.3. Reservoir capacity constraint

The operating volume of reservoir storage limit must lie in between minimum and maximum capacity limits, and is given by,

$$V_j^{min} \le V_{jt} \le V_j^{max} \tag{8}$$

where V_j^{min} and V_j^{max} are the minimum and maximum water volume of reservoir j.

2.3.4. Hydro water discharge rate limits

The hydro water discharge rate limit must lie in between its minimum and maximum operating limits, and is given by,

$$q_j^{min} \le q_{jt} \le q_j^{max} \tag{9}$$

where q_j^{min} and q_j^{max} are the minimum and maximum water discharge of hydro plant j.

The above objective function is solved using the Clustered Adaptive Teaching Learning Based Optimization (CATLBO) algorithm. The detailed description of CATLBO is presented in [29-30].

3. RESULTS AND DISCUSSION

To test the effectiveness of the proposed CATLBO algorithm for ST-HTS problem, a test system is considered same as in reference [29]. This system consists of multi-chain, four hydro plant cascade, and an equivalent thermal plant. The scheduling period considered is 1 day with hourly intervals. The hydraulic system considered is characterized by river transport delay between successive reservoirs, variable head hydro plants, variable natural inflow rates into each reservoir, prohibited operating zones of water discharge rates, variable load demand over scheduling interval. The quadratic fuel cost characteristics of the equivalent thermal unit is given by,

$$f(P_{it}) = 5000 + 19.2P_{it} + 0.002(P_{it})^2 \qquad (10)$$

The lower and upper power limits of this equivalent thermal generator/unit are 500 MW and 2500MW respectively, and for hydraulic units are 0 MW and 500 MW, respectively. Two different case studies are considered to demonstrate the effectiveness of the proposed CATLBO algorithm, and they are:
- Case 1: System with quadratic cost curve and without prohibited discharge zones effect.
- Case 2: System with prohibited discharge zones effect.

3.1. Case 1

This case considers quadratic cost curve without prohibited discharge zones effect. Table 1 shows the hourly hydro plant power outputs, and total thermal generation for Case 1. The minimum cost obtained with proposed CATLBO algorithm is 922266.04$. Hourly hydro plant discharge for Case 1 is reported in Table 2. Table 3 shows the optimum cost obtained with other techniques reported in the literature. The optimum costs obtained from the proposed CATLBO algorithm with that of dynamic programming (DP), Non-Linear Programming (NLP), Evolutionary Programming (IFEP), and Differential Evolution (DE), Local vision of PSO with inertia weight (LWPSO), Improved Particle Swarm Optimization (IPSO), and Modified Seeker Optimization Algorithm (MSOA) are presented in Table 3. The proposed approach yields better result than DP, NLP, IFEP, DE, IPSO, and MSOA, while satisfying the reservoir end-volume constraints.

Table 1. Hydro plant/reservoir power outputs and total thermal generation for Case 1

Hour	Hydro Power Generations (in MW)				Thermal Power Generations (MW)	Total Power Generation (MW)
	Plant 1	Plant 2	Plant 3	Plant 4		
1	85.148	57.882	0.000	200.099	1026.871	1370
2	88.215	52.434	0.000	187.755	1061.597	1390
3	80.254	53.918	0.000	173.733	1052.095	1360
4	76.980	58.045	0.000	156.791	998.185	1290
5	75.834	54.253	24.787	178.741	956.386	1290
6	70.845	56.180	28.849	198.957	1055.168	1410
7	71.231	55.984	31.343	217.440	1274.002	1650
8	75.211	62.406	33.459	234.185	1594.740	2000
9	76.535	65.957	35.067	239.065	1823.376	2240
10	80.162	68.374	35.103	243.061	1893.300	2320
11	79.033	67.003	36.762	246.302	1800.900	2230
12	80.313	71.901	37.744	251.400	1868.643	2310
13	79.697	71.747	37.633	264.148	1776.775	2230
14	80.301	70.973	37.054	272.010	1739.661	2200
15	80.288	74.391	37.460	268.170	1669.691	2130
16	79.874	74.002	36.663	270.423	1609.039	2070
17	77.822	75.436	38.921	277.736	1660.085	2130
18	73.754	75.949	43.197	282.941	1664.158	2140
19	77.105	73.088	46.268	285.244	1758.294	2240
20	75.352	76.823	49.141	288.920	1789.764	2280
21	74.489	77.298	50.637	295.627	1741.948	2240
22	74.706	67.918	52.728	299.730	1624.917	2120
23	58.742	69.544	54.584	294.779	1372.351	1850
24	55.033	70.443	56.069	295.213	1113.243	1590
Total Generation Cost = 922266.04 $						

Table 2. Hourly plant/reservoir discharge ($\times 10^4\ m^3$) for Case 1

Hour	Hydro Discharges ($\times 10^4\ m^3$of water)				Reservoir Volume ($\times 10^4\ m^3$of water)			
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 1	Plant 2	Plant 3	Plant 4
0	0	0	0	0	100.0	80.0	170.0	120.0
1	9.80	7.25	30.0	13.0	100.20	80.75	148.10	109.80
2	10.64	6.28	30.0	13.0	98.56	82.46	126.30	99.20
3	9.02	6.28	30.0	13.0	97.54	85.19	110.11	87.80
4	8.53	6.70	30.0	13.0	96.01	87.49	100.0	74.80
5	8.48	6.0	18.30	13.0	93.53	89.49	100.0	91.80
6	7.69	6.21	17.41	13.0	92.84	90.28	101.39	108.80
7	7.74	6.20	16.85	13.0	93.10	90.08	102.72	125.80
8	8.36	7.15	16.07	13.0	93.74	89.93	102.34	142.80
9	8.495	7.679	15.357	13.0	95.245	90.246	101.934	148.098
10	9.025	7.983	15.376	13.0	97.220	91.263	102.117	152.500
11	8.618	7.648	14.948	13.0	100.602	92.615	103.815	156.349
12	8.775	8.502	15.192	13.27	101.827	92.113	107.327	159.152
13	8.545	8.524	16.052	14.51	104.281	91.589	111.876	159.999
14	8.491	8.330	16.682	15.378	107.790	92.260	114.618	159.998
15	8.389	8.921	16.973	14.947	110.401	92.339	117.692	159.999
16	8.265	8.943	17.432	15.199	112.136	91.396	119.275	159.992
17	7.921	9.470	16.941	16.045	113.215	88.926	121.053	159.999
18	7.323	10.059	15.801	16.682	113.891	84.867	124.439	159.999
19	7.819	9.828	14.776	16.974	113.072	82.039	127.527	159.999
20	7.609	11.138	13.543	17.458	111.463	78.900	131.777	159.973
21	7.499	11.769	10.001	18.633	110.964	76.131	141.654	158.281
22	7.517	9.649	10.001	19.973	111.447	75.483	151.091	154.109
23	5.445	10.357	10.010	20.108	115.001	73.126	160.719	148.777
24	5.001	11.126	10.005	22.320	120	70	170	140

Table 3. Comparison of optimal costs for test system with quadratic cost and no prohibited discharge zones for Case 1

Algorithm	Minimum cost ($)	Algorithm	Minimum cost ($)
DP [6]	928919.15	LWPSO [32]	925383.8
GA [3]	926707.00	DE [6]	923574.31
NLP [6]	924249.48	MDE [10]	922555.44
FEP [31]	930267.92	IPSO [6]	922553.49
CEP [31]	930166.25	MSOA [9]	922355
IFEP [4]	930129.82	CATLBO	922266.04

3.2. Case 2

Table 4 presents the hourly hydro plant power outputs, thermal power generation, and total power generation for Case 2. The minimum thermal generation cost obtained in this case is 912772.3159$. The optimal hydro discharge and storage volumes obtained from proposed CATLBO algorithm are presented in Table 5.

Table 4. Hydro plant power outputs and total thermal generation for Case 2

Hour	Hydro Power Generations (in MW)				Thermal Power Generations (MW)	Total Power Generation (MW)
	Plant 1	Plant 2	Plant 3	Plant 4		
1	85.845	63.421	0.000	203.300	1017.434	1370
2	91.675	55.636	0.000	188.290	1054.399	1390
3	80.914	51.355	0.000	173.338	1054.393	1360
4	86.592	66.660	0.000	156.278	980.470	1290
5	68.047	58.834	41.597	178.002	943.519	1290
6	67.146	53.384	0.000	198.094	1091.376	1410
7	53.623	70.289	33.940	215.990	1276.159	1650
8	63.791	3.649	41.577	232.178	1608.805	2000
9	82.634	52.633	41.771	232.411	1830.551	2240
10	85.441	76.609	42.762	247.716	1867.471	2320
11	85.206	53.945	44.992	252.256	1793.601	2230
12	56.086	55.386	45.650	248.401	1904.478	2310
13	87.535	57.645	40.634	250.579	1793.608	2230
14	66.333	58.746	33.940	247.386	1793.595	2200
15	77.845	71.640	47.802	250.005	1682.708	2130
16	69.665	61.959	45.572	247.070	1645.733	2070
17	88.992	85.213	41.018	269.019	1645.758	2130
18	75.424	82.342	42.297	294.238	1645.699	2140
19	87.270	56.023	46.693	256.419	1793.596	2240
20	55.328	85.618	51.138	294.337	1793.579	2280
21	73.200	84.492	52.619	273.050	1756.638	2240
22	73.829	77.253	54.759	305.385	1608.774	2120
23	78.332	73.558	56.046	292.006	1350.059	1850
24	67.311	45.117	58.831	290.436	1128.306	1590
Total Generation Cost = 912772.3159 $						

Table 5. Hourly plant discharge ($\times 10^4\ m^3$) for Case 2

Hour	Hydro Discharges ($\times 10^4\ m^3$of water)				Reservoir Volume ($\times 10^4\ m^3$of water)			
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 1	Plant 2	Plant 3	Plant 4
0	0	0	0	0	100.000	80.000	170.000	120.000
1	9.964	8.274	29.659	13.420	100.036	79.726	148.441	109.380
2	11.774	6.899	29.983	13.141	97.263	80.827	126.658	98.639
3	9.253	6.024	29.725	13.045	96.010	83.804	110.897	87.194
4	10.934	8.336	29.140	13.046	92.076	84.468	103.804	74.148
5	7.374	6.974	13.282	13.069	90.702	85.494	109.674	90.738
6	7.251	6.109	28.674	13.048	90.451	86.385	101.958	107.674
7	5.327	9.124	16.236	13.001	93.124	83.260	104.432	124.397
8	6.533	6.340	12.494	13.014	95.591	83.921	108.163	140.523
9	9.601	6.042	12.214	13.011	95.990	85.879	108.384	140.794
10	10.138	10.228	12.970	13.142	96.852	84.650	112.072	156.325
11	9.911	6.100	11.739	13.350	98.941	87.550	117.274	159.212
12	5.329	6.167	13.694	13.012	103.612	89.383	121.760	158.695
13	9.992	6.368	17.342	13.320	104.620	91.015	128.558	157.589
14	6.426	6.336	18.742	13.007	110.195	93.679	124.245	157.552
15	7.923	8.253	14.097	13.410	113.272	94.426	129.307	155.881
16	6.732	6.651	15.405	13.063	116.540	95.775	128.696	156.512
17	9.681	11.259	17.125	15.173	115.858	91.516	127.831	158.681
18	7.502	11.339	16.713	18.309	116.357	86.178	128.102	159.114
19	9.443	6.459	15.106	13.749	113.914	86.719	130.329	159.462
20	5.069	13.200	12.910	18.767	114.845	81.519	137.179	156.099
21	7.232	14.291	10.094	15.765	114.613	76.228	149.868	157.459
22	7.303	12.495	11.740	21.270	115.310	72.733	151.655	152.902
23	7.915	12.380	10.784	19.711	116.394	68.353	162.303	148.296
24	6.394	6.353	13.897	21.206	120	70	170	140

4. CONCLUSION

In this paper, a new Clustered Adaptive Teaching Learning Based Optimization (CATLBO) algorithm is developed to solve the Short-Term Hydro Thermal Scheduling (ST-HTS) problem. The proposed algorithm is tested on a standard sample test system considering three different case studies. This algorithm has provided the best results compared to other conventional and meta-heuristic algorithms like Dynamic Programming (DP), Non-Linear Programming (NLP), Evolutionary Programming (IFEP), Differential Evolution (DE), Improved Particle Swarm Optimization (IPSO), and Modified Seeker Optimization Algorithm (MSOA) reported in the literature. This CATLBO algorithm can easily be extended to any other complex optimization problems faced by the utilities.

ACKNOWLEDGEMENTS

This research work has been carried out based on the support of “Woosong University's Academic Research Funding - 2019”.

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