Scholars Journal of Engineering and Technology (SJET) **ISSN 2321-435X (Online)**
Sch. J. Eng. Tech., 2015; 3(3A):244-251 **ISSN 2347-9523 (Print)**
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Research Article

Sinusoidal Migration of Biogeography based Optimization for Short Term Hydrothermal Scheduling

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Abstract: This paper presents a sinusoidal migration of biogeography based optimization for solving short term hydrothermal scheduling (STHTS) problem. This is one of the complex and hard to solve problems in power system field due to its nonlinear, dynamic, non-separable and nonconvex nature. Biogeography based optimization (BBO) is a powerful optimization technique, originated on the subject of biological species distribution. A mathematical formulation of the sinusoidal model of biogeography based optimization (SMBBO) is described and how biological species survive from one habitat to another habitat and gets annihilated. The proposed SMBBO approach is found to be accurate, robust, reliable and has ability to circumvent from local optima. This SMBBO approach is validated on a test system consisting of cascaded nine hydroelectric plants and an equivalent thermal plant with and without valve point loading effect. The simulation results show that the proposed approach is providing better results in terms of minimum cost and computational time as compared to linear migration model of BBO, particle swarm optimization (PSO), differential evolution (DE) and genetic algorithm (GA).
Keywords: Short term hydrothermal scheduling, cascaded multi reservoir systems, biogeography based optimization, sinusoidal migration

INTRODUCTION

The short term hydrothermal scheduling (STHTS) problem is an important and challenging constrained optimization problem in electrical power systems. The generation of hydro plant resources is the natural water sources with the almost insignificant operational cost. Therefore, the STHTS problem is intended to minimize the total production cost of thermal plants over the scheduled horizon while satisfying all diverse constraints. In the hydrothermal system, considering a cascading nature of reservoirs, water time delays between the linked reservoirs, valve point loading effects of thermal plants. Therefore, the STHTS problem becomes a distinctive large size, nonlinear and non-convex constrained optimization problem. A wide variety of optimization methods have been successfully employed to solve STHTS problems in the past decades. More or less of these formal methods are gradient search method [1], network flow programming [2], dynamic programming [3], two phase neural network [4], etc. These methods are not able to provide optimal results due to their difficulty in dealing with large scale and non-convexity, slow convergence and inability to deal with constraints of STHTS problem. Different from these methods, the heuristic approaches have been presented to solve STHTS problem, such as genetic algorithm (GA) [5], differential evolution (DE) [6] and particle swarm optimization (PSO) [7], etc. The heuristic algorithms have the capability to handle large size problems and also get a high quality solution in less execution time compared to deterministic methods. However, these methods do not guarantee to provide global optimal solutions all the time due to lack of mechanism between exploration and exploitation capabilities in the search space. Evolutionary approaches like GA, DE, PSO, etc. the solutions will die at the end of the evolutionary process, forming a group of similar things and the existence of the crossover operation initially good fitness solutions may lose their quality in later stages. These methods applied to large size optimization problems may converge to local optimum solutions and may reduce the solution accuracy with large computational time.

In recent years, a powerful heuristic optimization method named as a biogeography based optimization (BBO), which has been demonstrated by Don Simon [8] and applied for solving various power system optimization problems successfully [10]. BBO works on two important mechanisms such as: migration and mutation. There is no crosser operation in BBO, which results in the gradual improvement of solutions as the search process continues through migration. However, the linear migration process in BBO cannot exploit the local information of species in the search space. In society to heighten the operation of searching global optimal solution and accelerate up the convergence process, a sinusoidal migration is integrated into BBO called sinusoidal migration BBO (SMBBO) for solving STHTS problems. The sinusoidal migration is capable of exploring fresh and more promising solutions and present a right direction to the global optimal region. Additionally, the advantage of a mutation operation in SMBBO, solutions does not lead the tendency to bunch together in similar groups. Moreover, the SMBBO approach incorporates the features of elitism and gives an advantage over other evolutionary approaches. Therefore, BBO has the strongest global search capability and efficient in dealing with all constraints in STHTS problem had nonlinear and non-convex characteristics. In order to verify the accuracy and feasibility of the proposed SMBBO method applied to a test system comprises of nine hydro plants and one equivalent thermal plant. Thus, the obtained results demonstrate the proposed method is capable to provide better solutions as compared to other methods.

PROBLEM FORMULATION

The main objective function and all associated constraints of the STHTS problem are formulated as follows [7]:

Objective Function

The objective function of short term hydrothermal scheduling of Nh hydro units and Ng thermal units over T time intervals is expressed as a sum of quadratic and a sinusoidal function. The STHTS problem is to minimize the following composite total production cost function can be described as follows:

$$TPC = \sum_{t=1}^{T} \sum_{i=1}^{Ng} a_i + b_i Pg_i^t + c_i \left(Pg_i^t\right)^2 + \left| d_i \times \sin\left\{ e_i \times \left(Pg_i^{\min} - Pg_i^t \right) \right\} \right| \tag{1}$$

where TPC is the total production cost of thermal plants in \$/h, a_i, b_i, c_i, d_i and e_i are thermal generation coefficients of i^{th} plant, T is the total scheduling time horizon and Pg_i^t is the thermal generation of i^{th} plant at t^{th} time interval.

Generation Load Power Balance

$$\sum_{i=1}^{Ng} Pg_i^t + \sum_{j=1}^{Nh} Ph_j^t = Pd^t \tag{2}$$

where Ph_j^t is the thermal generation of j^{th} plant at t^{th} time interval and Pd^t is the power demand at t^{th} time interval.

Hydro and Thermal Plant Operating Limits

Thermal plants can generate power between specified operating minimum and maximum limits are expressed as

$$\begin{aligned} Pg_i^{\min} \le Pg_i^t \le Pg_i^{\max} \quad & i \in Ng \\ Ph_j^{\min} \le Ph_j^t \le Ph_j^{\max} \quad & j \in Nh \end{aligned} \tag{3}$$

where $Pg_i^{\min}, Pg_i^{\max}$ are the minimum and maximum limits of i^{th} thermal plant and $Ph_j^{\min}, Ph_j^{\max}$ are the minimum and maximum limits of j^{th} hydro plant.

Hydro Power Generation

The generation of hydro power is a function of both water discharge rate and reservoir storage volume.

$$Ph_j^t = c_{1j}\left(V_j^t\right)^2 + c_{2j}\left(q_j^t\right)^2 + c_{3j} V_j^t q_j^t + c_{4j} V_j^t + c_{5j} q_j^t + c_{6j} \tag{4}$$

where $c_{1j}, c_{2j}, c_{3j,} c_{4j}, c_{5j}$ and c_{6j} are the hydro power generation coefficients of the j^{th} hydro plant, V_j^t is the reservoir storage volume of j^{th} hydro plant and q_j^t is the water discharge rate of j^{th} hydro plant at t^{th} time interval.

Reservoir Storage Volume Capacity

The reservoir storage volume limits must lie between the maximum and minimum as

$$V_j^{\min} \le V_j^t \le V_j^{\max} \tag{5}$$

where $V_j^{\min}, V_j^{\max}$ are minimum and maximum reservoir volume storage limits of j^{th} hydro plant.

Water Discharge Rate Limits

The water discharge rate must lie in between maximum and minimum operating limits as

$$q_j^{\min} \le q_j^t \le q_j^{\max} \tag{6}$$

where $q_j^{\min}, q_j^{\max}$ are the minimum and maximum water discharge limits of j^{th} hydro plant.

Hydraulic Continuity Equation

The water balance equation models the dynamic flows of the reservoir.

$$V_j^{t+1} = V_j^t + I_j^t - q_j^t + \sum_{m=1}^{Nu_j} q_m^{t-r_j^m} \qquad j \in Nh \qquad (7)$$

where I_j^t is the inflow rate of j^{th} hydro plant, $q_m^{t-r_j^m}$ is the water flow from m^{th} to j^{th} reservoir during the time delay r_j^m ; r_j^m is the water transportation delay from m^{th} to j^{th} reservoir; Nu_j is the number of upstream plants above to the j^{th} hydro plant.

Start and End Reservoir Storage Volumes

The begin and end reservoir storage volume limits are considered to be known, so the reservoir storage volume limits must satisfies as

$$V_j^0 = V_j^{Start}, \qquad V_j^T = V_j^{End} \qquad (8)$$

where V_j^0, V_j^T are the reservoir storage volume of j^{th} hydro plant at 0 and T time intervals; V_j^{Start}, V_j^{End} are start and end reservoir storage volume limits of j^{th} hydro plant.

SOLUTION TECHNIQUE

Biogeography based optimization has been developed based on the concept of biogeography [8]. It is also a population based optimization technique, where the candidate solution is represented as a vector of habitats. Each variable in the habitat array is considered as suitability index variable (SIV).

Representation of Individuals

The suitability index variables $(SIV's)$ for the short term hydrothermal scheduling (STHTS) problem are hourly water discharge rates, which are used to represent as a solution.

$$H_k = \left[q_1^1, \ldots, q_{Nh}^1, \ldots, q_1^T, \ldots, q_{Nh}^T \right] \qquad (9)$$

All these variables in each habitat are represented as real values. The total habitat matrix set is represented as follows:

$$\begin{aligned} &H_k = \left[SIV_k^1, SIV_k^2, \ldots, SIV_k^d, \ldots, SIV_k^n \right] \\ &k = 1,2,3,\ldots,S; \qquad d = 1,2,3,\ldots,D \end{aligned} \qquad (10)$$

where H_k is the position of the k^{th} habitat. SIV_k^d represents the water discharge rate of d^{th} dimension of the k^{th} habitat set H_k and D is the number of $SIV's$ are chosen as $D = T \times Nh$. The habitat suitability index (HSI) of each habitat is calculated, which corresponds to the fitness function of other evolutionary approaches.

$$HSI_k = f\left(SIV_k^1, SIV_k^2, \ldots, SIV_k^d, \ldots, SIV_k^n \right) \qquad (11)$$

In the proposed approach, high HSI solutions represent a good quality solution and low HSI solutions represent an inferior solution. The good quality solution has a tendency to share their features with inferior solution which helps to acquire quality features of better quality solution [9]. BBO works on two important strategies: migration and mutation process. In this approach, each habitat represents a candidate solution and gets updated by the process of migration and mutation. The migration and mutation strategies control the exploration and exploitation capabilities of the search space.

Migration

Migration is the movement of species from one habitat to another. Emigration is the act of departing one's native region, while immigration is the arrival of new species into habitats. Each habitat is representing as a solution characterized by its immigration rate λ and emigration rate μ. A better solution likes a higher emigration μ and lower immigration rate λ, suggesting that it is likely to be altered and calculated using different migration models. The concept of the sinusoidal migration model has been explored in BBO (SMBBO) based on the shape of migration curve [9].

$$\lambda_k = \frac{I}{2}\left(\cos\left(\frac{k\pi}{n} \right) + 1 \right) \qquad (12)$$

$$\mu_k = \frac{E}{2}\left(-\cos\left(\frac{k\pi}{n}\right)+1\right) \qquad (13)$$

where I is the maximum possible immigration rate, k is the number of species in habitat, n is the largest number of species in habitat and E is the maximum possible emigration rate. The immigration rate and emigration rate are changed slowly from their extreme values when the habitat has a large number or a small number of species, while the medium number of species, the emigration and immigration rates are changed from their equilibrium values. The migration process in SMBBO yields changes in the existing solutions after the recombination process is completed, whereas this is not the case in other evolutionary approaches where a new solution is created.

Mutation

Mutation process is employed to enhance the diversity of habitats which helps to reduce the chances of getting premature convergence. Mutation rates organized probabilistically which modifies the solutions randomly based on the habitat's priori species count probability. The species count probability form P_k from λ_k and μ_k. If habitat H_k is selected for mutation then it executes randomly chosen SIV variable based on its associated probability P_k. The mutation rate is calculated as follows:

$$m_k = p_{\mathrm{m}}\left(1-\frac{P_k}{P_{\max}}\right) \qquad (14)$$

where p_{m} is the mutation probability rate, P_k is probability of a habitat that contain k number of species and $P_{\max}$ is the maximum probability.

SMBBO APPROACH APPLIED TO STHTS PROBLEM

The proposed sinusoidal migration of biogeography based optimization (SMBBO) approach is applied to solve STHTS in order to find the optimum generation schedule while satisfying various operational constraints over the scheduled time horizon. The sequential steps of the proposed SMBBO approach are described in below mentioned steps

Step 1: Initialization of proposed SMBBO parameters like maximum immigration rate, modification probability, number of generations, maximum emigration rate, total number of habitats, mutation probability rate and number of suitability index variables.

Step 2: Generate habitat, which represents a potential solution of the problem while satisfying all constraints. The hourly water discharge rates are represented as suitability index variables over the entire scheduling period.

Step 3: In order to satisfy the equality and inequality constraints by making dependent thermal generation. The system load demand for d^{th} dependent thermal power generation can be calculated as follows:

$$P_{gd}^t = PD^t - \sum_{\substack{i=1 \\ i\neq d}}^{Ng} P_{gi}^t - \sum_{j=1}^{Nh} P_{hj}^t \qquad (15)$$

This will result in the set of feasible habitat solutions according to limits of decision variables that satisfy all the operational constraints.

Step 4: Compute the total production cost of each individual habitat in the population. The HSI value is calculated for each habitat of the population for a given immigration rate and emigration rate. Those habitats whose total production cost is minimum, i.e. high HSI values are to be considered as a valid species in the short term hydrothermal scheduling problem. The valid species based on HSI values are kept as an elite habitat set in order to retain the best solution in the population.

Step 5: Migration process on each non-elite habitat is performed and modified probabilistically through emigration rate and immigration rate. The feasible solution is achieved after calculation of HSI for each modified habitat. After migration process a new habitat set is developed.

Step 6: The mutation process is carried out probabilistically on each non-elite habitat, and corresponding HSI values of each habitat are calculated. If the mutation rate is greater than the randomly generated number, then the mutation is performed on that habitat. The feasibility of solution should be verified for modified habitats; if it doesn't satisfy the constraints, then simply replaced the habitat set with all constraints.

Step 7: Check whether the maximum number of iterations is exceeded, then stop the criteria and print the optimal generation schedule. Otherwise increment the iteration number and go back to step 3.

SIMULATION RESULTS

To demonstrate the effectiveness of the SMBBO approach, it is applied on a test system which comprises of nine hydroelectric plants and one equivalent thermal plant. The test system considering the cascading nature of hydro plant and variation in inflows depicted in Fig.1.

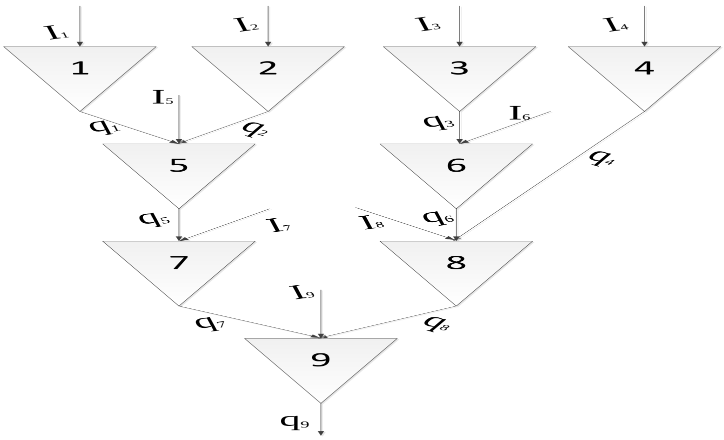

Fig.1. Hydraulic network of the nine reservoir test system

The scheduled time horizon of the test system is selected as one day with 24 time intervals of each 1 hour period. The input data of hydro plant configurations are given in Appendix. Meanwhile, standard biography based optimization (BBO), particle swarm optimization (PSO), differential evolution (DE) and genetic algorithm (GA) are utilized for solving the same test system and to compare their performance with the proposed SMBBO approach.

The simulations are carried out on a PC (core i5 processor, 2.67 GHz, 4GB RAM) and coding is implemented using MATLAB 7.10.The performance of the SMBBO influences more of the control parameters, which are needed to be determined before implementation. The optimal choice of control parameters is dependent on the system characteristics. In this simulation, 50 random trials with different initial populations are carried out to choose the control parameters and test the validity of the proposed SMBBO approach. After a series of runs conducted with different values of control parameters, the optimal control parameters are selected such as number of habitats S =50, maximum number of iterations= 300, maximum immigration rate I =1, maximum emigration rate E =1 and mutation probability rate p_{m} =0.1. The population size=50 and maximum number of iterations=300 have been selected for GA, DE and PSO. In case of GA, crossover rate=0.75 and mutation rate=0.01 have been selected. In DE, the crossover rate and scaling factor have been selected as 0.3 and 0.85. In case of PSO, $c_1 = c_2 = 2$ and inertial weight 0.4 to 0.9 respectively.

Case I: The system is considered without valve point loading effect. The quadratic smooth production cost function of the composite thermal plant is represented as

$$TPC = \sum_{t=1}^{T} \sum_{i=1}^{Ng} a_i + b_i Pg_i^t + c_i \left(Pg_i^t \right)^2 \qquad (16)$$

The thermal production cost function coefficients are a_i =5000, b_i =19.2, and c_i =0.002. The minimum and maximum generation limits of thermal plant are taken as 30MW and 1500MW, respectively. The proposed SMBBO approach, BBO, PSO, DE and GA are implemented to solve STHTS problem of the test system and the best optimal production cost result obtained with these methods are given in Table 1. It can be concluded that the proposed SMBBO approach yields better quality results of production cost **366661.20 $** and average CPU time **48.91seconds** as compared other approaches.

Table-1: Comparison of Total Production Cost of Different Methods for Case 1

Approaches	Total Production Cost ($)	Average CPU time (s)
GA	389617.65	92.43
DE	381905.16	57.28
PSO	379653.80	48.98
BBO	375508.63	50.37
SMBBO	366661.20	48.91

Case II: The non-smooth production cost function of the equivalent thermal plant considering valve point loading effect is represented as in equation (1) and the coefficients are a_i =5000, b_i =19.2, c_i =0.002, d_i =700 and e_i =0.085. The minimum and maximum generation limits of thermal plant, in this case are the same as case I. The optimal results obtained through proposed SMBBO approach resulted in the production cost value equal to **382622.03 ($)** and corresponding average CPU time **49.34 seconds**.

Table-2: Comparison of Total Production Cost of Different Methods for Case II

Approaches	Total Production Cost ($)	Average CPU time (s)
GA	397743.93	92.47
DE	396423.73	58.10
PSO	393268.84	49.86
BBO	390439.15	50.93
SMBBO	382622.03	49.34

The total production cost and execution time comparison of different approaches are given in Table 2 and the convergence characteristics are depicted in Fig. 2.It is seen from Fig. 2, the cost convergence characteristics of SMBBO approach is decreasing rapidly in the beginning and is stabilized at minimum value. The same test system is also solved using BBO with linear migration model, PSO, DE and GA approaches to validate the results obtained from the proposed SMBBO approach. Finally, the simulation results are obtained for optimal generation scheduling of SMBBO approach given in Table 3 and it's also been observed that all optimal schedule results satisfy all the constraints. Thus, the results obtained using SMBBO approach performed better than the other approaches in terms of production cost and average CPU time. This signifies that the proposed SMBBO approach is a competitive approach for solving constrained STHTS problems, including various constraints. Also, in order to identify the migration models effect on BBO is examined on the same test system by keeping the same parameter values. It has been observed that sinusoidal migration is superior to linear migration, because due to more influence of emigration rate on BBO approach than immigration rate.

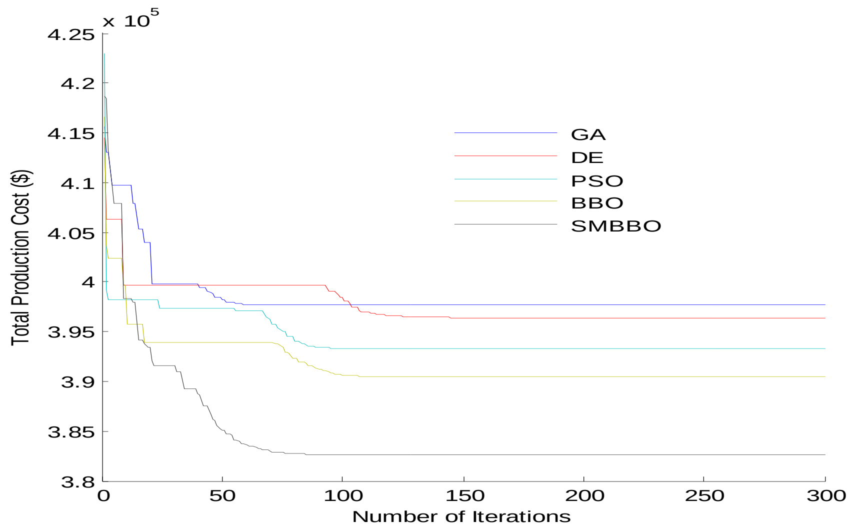

Fig. 2.Cost convergence characteristics of Case II

Table 3. Optimal Hourly Hydrothermal Generation Schedule

Hour	Load Demand	Hydro 1 (MW)	Hydro 2 (MW)	Hydro 3 (MW)	Hydro 4 (MW)	Hydro 5 (MW)	Hydro 6 (MW)	Hydro 7 (MW)	Hydro 8 (MW)	Hydro 9 (MW)	Thermal (MW)
1.	1370	76.72	69.23	55.68	87.93	93.43	222.78	233.02	272.41	150.31	108.48
2.	1390	77.75	84.08	54.70	102.25	94.31	226.19	227.74	249.01	133.01	140.95
3.	1360	85.55	69.08	59.11	90.06	86.78	205.54	220.10	294.19	182.71	66.90
4.	1290	64.67	65.26	63.06	86.76	87.38	154.68	201.66	276.76	223.56	66.20
5.	1290	91.34	65.66	62.94	105.64	95.19	160.53	156.00	278.30	207.45	66.94
6.	1410	75.02	70.29	53.57	101.96	96.47	165.55	221.15	299.97	222.09	103.92
7.	1650	69.24	84.02	62.73	95.33	97.95	202.37	222.33	327.14	227.15	261.74
8.	2000	100.07	77.86	61.86	106.44	94.11	192.11	216.94	290.18	239.19	621.24
9.	2240	99.57	86.78	66.16	107.35	96.31	187.72	211.92	307.28	271.09	805.83
10.	2320	106.51	79.32	62.44	110.85	98.46	226.62	222.34	330.26	278.17	805.02
11.	2230	91.48	87.63	60.53	110.39	96.30	164.63	207.63	326.16	279.17	806.08
12.	2200	107.9	79.01	69.12	107.92	97.93	196.38	225.20	347.43	306.07	773.05
13.	2130	98.41	74.13	70.00	119.53	97.52	198.66	212.81	317.02	240.51	801.41
14.	2070	99.71	77.29	62.07	92.44	91.15	196.19	180.14	341.30	290.83	768.89
15.	2130	77.32	86.49	71.27	86.59	94.87	228.38	172.17	338.68	278.98	695.25
16.	2070	102.24	97.09	69.10	113.6	93.20	179.89	118.64	329.56	274.89	691.79
17.	2130	80.36	85.61	64.62	96.01	95.61	190.54	211.04	337.76	310.14	658.31
18.	2140	105.52	89.05	70.70	104.87	85.67	169.68	189.73	323.46	232.13	769.20
19.	2240	98.61	96.64	64.78	93.34	90.32	200.98	181.56	349.06	258.56	806.16
20.	2280	99.09	96.52	65.46	129.43	84.84	190.28	175.99	335.76	259.52	843.12
21.	2240	107.35	91.23	71.39	96.04	81.18	168.74	206.07	363.44	211.43	843.12
22.	2120	104.75	99.45	70.66	115.34	85.04	187.68	186.58	357.02	292.28	621.19
23.	1850	94.18	107.11	77.99	100.85	83.27	220.04	212.66	365.86	262.36	325.68
24.	1590	102.66	104.80	75.58	103.44	72.58	212.86	150.33	328.31	224.65	214.79
Total Production Cost							**382622.03 $**				

CONCLUSIONS

In this paper, a sinusoidal migration of biogeography based optimization has been presented for solving short term hydrothermal scheduling problem and its performance is evaluated on a test system consists of cascaded nine hydro plants and one equivalent thermal plant. To enhance the exploration and exploitation capability of search space and to avoid premature convergence, the sinusoidal migration model has been used in biogeography based optimization. The robustness of the proposed SMBBO has been compared with a linear migration model of BBO, particle swarm optimization, differential evolution and genetic algorithm approach. The results obtained by the proposed SMBBO approach have shown that minimum total production cost and less execution time as compared to BBO and other approaches.

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Appendix. Input Data of Hydro plants

Hydro unit parameters	Hydro 1	Hydro 2	Hydro 3	Hydro 4	Hydro 5	Hydro 6	Hydro 7	Hydro 8	Hydro 9
c_{1j}	-0.0042	-0.004	-0.0038	-0.0042	-0.0046	-0.003	-0.0014	-0.0028	-0.0018
c_{2j}	-0.42	-0.3	-0.42	-0.3	-0.24	-0.31	-0.22	-0.3	-0.42
c_{3j}	0.03	0.015	0.012	0.032	0.014	0.027	0.015	0.029	0.025
c_{4j}	0.9	1.14	1.2	1	0.55	1.44	0.5	1.56	1.25
c_{5j}	10	9.5	8	10	9.5	14	12	13	12.5
c_{6j}	-50	-70	-70	-50	-30	-80	-60	-80	-80
$V_j^{\min}\left(\times 10^3 m^3\right)$	50	50	50	50	50	50	50	100	100
$V_j^{\max}\left(\times 10^3 \mathrm{m}^3\right)$	150	150	150	150	200	300	350	350	340
$V_j^{initial}\left(\times 10^3 \mathrm{m}^3\right)$	100	90	95	85	140	140	200	150	140
$V_j^{final}\left(\times 10^3 \mathrm{m}^3\right)$	140	140	140	140	170	160	210	220	240
$q_j^{\min}\left(\times 10^3 \mathrm{m}^3\right)$	5	6	5	5	15	5	10	10	25
$q_j^{\max}\left(\times 10^3 \mathrm{m}^3\right)$	15	15	13	12	30	15	30	20	40
Nu	0	0	0	0	2	1	1	2	2
$I_j\left(\times 10^3 \mathrm{m}^3/\mathrm{h}\right)$	12	11	10	11	3	1	1	0.2	0
$Ph_j^{\min}\,(\mathrm{MW})$	0	0	0	0	0	0	0	0	0
$Ph_j^{\max}\,(\mathrm{MW})$	500	500	500	500	500	500	500	500	500