

Solving Short Term Multi Chain Hydrothermal Scheduling Problem by Artificial Bee Colony Algorithm

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ABSTRACT

This paper presents an artificial bee colony algorithm for solving optimal short term hydrothermal scheduling problem. To demonstrate the effectiveness of the proposed algorithm, hydrothermal test system consists of three thermal units and four cascaded hydro power plants has been tested. The valve point loading effect is taken into consideration. In order to show the feasibility and robustness of the proposed algorithm, a wide range of thermal and hydraulic constraints are taken into consideration. The numerical results obtained by ABC algorithm are compared with those obtained from other methods such as genetic algorithm (GA), simulated annealing (SA), evolutionary programming (EP) and constriction factor based particle swarm optimization (CFPSO) technique to reveal the validity and verify the feasibility of the proposed method. The experimental results indicate that the proposed algorithm can obtain better schedule results with minimum execution time when compared to other methods.

Keywords: Hydrothermal Generation Scheduling, Artificial Bee Colony, Valve Point Loading Effect

I. INTRODUCTION

The hydrothermal scheduling problem is a non linear programming problem including a non linear objective function and subjected to a mixture of linear and non linear operational constraints. Since the operating cost of hydro electric power plant is very low compared to the operating cost of thermal power plant, the integrated operation of the hydro and thermal plants in the same grid has become the more economical [1]. The primary objective of the short term hydrothermal scheduling problem is to determine the optimal generation schedule of the thermal and hydro units to minimize the total operation cost of the system over the scheduling time horizon subjected to a variety of thermal and hydraulic constraints. The hydrothermal generation scheduling is mainly concerned with both hydro unit scheduling and thermal unit dispatching. Since there is no fuel cost associated with the hydro power generation, the problem of minimizing the total production cost of hydrothermal scheduling problem is achieved by minimizing the fuel cost of thermal power plants under the various constraints of the system [2]. Several mathematical optimization techniques have been used to solve short

term hydrothermal scheduling problems [3]. In the past, hydrothermal scheduling problem is solved using classical mathematical optimization methods such as dynamic programming method [4-5], lagrangian relaxation method [6-7], mixed integer programming [8], interior point method [9], gradient search method and Newton raphson method [2]. In these conventional methods simplified assumptions are made in order to make the optimization problem more tractable. Thus, most of conventional optimization techniques are unable to produce optimal or near optimal solution of this kind of problems. The execution time of these methods increases with the increase of the dimensionality of the problem. The most common optimization techniques based upon artificial intelligence concepts such as evolutionary programming [10-11], simulated annealing [12-13], differential evolution [14], artificial neural network [15-16], genetic algorithm [17 -19], particle swarm optimization [20-23], bacterial foraging algorithm [24] and artificial bee colony algorithm [25-27] have been given attention by many researchers due to their ability to find an almost global or near global optimal solution for short term hydrothermal scheduling problems under various operating constraints of the

system. The ABC algorithm is a population based optimization technique proposed by Devis Karaboga in 2005. It mimics the intelligent behaviour of honey bees. In ABC algorithm, the colony of artificial bee consists of three groups of bees: employed bees associated with specific food sources, onlooker bees watching the dance of employed bees within the hive to choose a food source and scout bees searching for food sources randomly. Both scouts and onlookers are also called unemployed bees. The first half of the colony consists of the employed artificial bees and the second half includes the onlookers. Compared to other evolutionary computation techniques, the ABC algorithm is simple and robust and can solve optimization problems quickly with high quality solution and stable convergence characteristic.

II. Objective Function and Operational Constraints

The main objective of short term hydro thermal scheduling problem is to minimize the total fuel cost of thermal power plants over the optimization period while satisfying all thermal and hydraulic constraints. The objective function to be minimized can be represented as follows:

$$FT = \sum_{t=1}^T \sum_{i=1}^N nt F_1^t(P_{gi}^t) \quad (1)$$

In general, the fuel cost function of thermal generating unit i at time interval t can be expressed as a quadratic function of real power generation as follows:

$$F_1^t(P_{gi}^t) = a_i(P_{gi}^t)^2 + b_i P_{gi}^t + c_i \quad (2)$$

Where P_{gi}^t is the real output power of thermal generating unit i at time interval t in (MW), $F_1^t(P_{gi}^t)$ is the operating fuel cost of thermal unit i in (\$/hr), FT is the total fuel cost of the system in (\$), T is the total number of time intervals for the scheduling horizon, nt is the numbers of hours in scheduling time interval t , N is the total number of thermal generating units, a_i, b_i and c_i are the fuel cost coefficients of thermal generating unit i .

By taking the valve point effects of thermal units into consideration, the fuel cost function of thermal power plant can be modified as:

$$F_{i,v}^t(P_{gi}^t) = a_i(P_{gi}^t)^2 + b_i P_{gi}^t + c_i + \left| e_i \times \sin(f_i \times (P_{gi}^{\min} - P_{gi}^t)) \right| \quad (3)$$

Where $F_{i,v}^t(P_{gi}^t)$ is the fuel cost function of thermal unit i including the valve point loading effect and f_i, e_i are the fuel cost coefficients of generating unit i with valve point loading effect.

The minimization of the objective function of short term hydrothermal scheduling problem is subject to a number of thermal and hydraulic constraints. These constraints include the following:

1) Real Power Balance Constraint: The total active power generation from the hydro and thermal plants must be equal to the total load demand plus transmission line losses at each time interval over the scheduling period.

$$\sum_{i=1}^N P_{gi}^t + \sum_{j=1}^M P_{hj}^t = P_D^t + P_L^t \quad (4)$$

Where, P_D^t is the total load demand during the time interval t in (MW), P_{hj}^t is the power generation of hydro unit j at time interval t in (MW), P_{gi}^t is the power generation of thermal generating unit i at time interval t in (MW), M is the number of hydro units and P_L^t represents the total transmission line losses during the time interval t in (MW). For simplicity, the transmission power loss is neglected in this paper.

2) Thermal Generator Limit Constraint: The inequality constraint for each thermal generator can be expressed as:

$$P_{gi}^{\min} \leq P_{gi}^t \leq P_{gi}^{\max} \quad (5)$$

Where P_{gi}^{\min} and P_{gi}^{\max} are the minimum and maximum power outputs of thermal generating unit i in (MW), respectively.

3) Hydro Generator Limit Constraint: The inequality constraint for each hydro unit can be defined as:

$$P_{hj}^{\min} \leq P_{hj}^t \leq P_{hj}^{\max} \quad (6)$$

Where P_{hj}^{\min} and P_{hj}^{\max} are the minimum and maximum power generation of hydro unit j in (MW), respectively.

4) Reservoir Storage Volume Constraint:

$$V_{hj}^{\min} \leq V_{hj}^t \leq V_{hj}^{\max} \quad (7)$$

Where V_{hj}^{\min} and V_{hj}^{\max} are the minimum and maximum storage volume of reservoir j, respectively.

5) Water Discharge Rate Limit Constraint:

$$q_{hj}^{\min} \leq q_{hj}^t \leq q_{hj}^{\max} \quad (8)$$

Where q_{hj}^{\min} and q_{hj}^{\max} are the minimum and maximum water discharge rate of reservoir j, respectively

6) Initial and Final Reservoir Storage Volume Constraint:

This constraint implies that the desired volume of water to be discharged by each reservoir over the scheduling period should be in limit.

$$V_{hj}^0 = V_{hj}^{\text{begin}} = V_{hj}^{\max} \quad (9)$$

$$V_{hj}^T = V_{hj}^{\text{end}} \quad (10)$$

Where V_{hj}^{begin} and V_{hj}^{end} are the initial and final storage volumes of reservoir j, respectively.

7) Water Dynamic Balance Constraint: The water continuity equation can be represented as:

$$V_{hj}^t = V_{hj}^{t-1} + I_{hj}^t - q_{hj}^t - S_{hj}^t + \sum_{u=1}^{R_{uj}} (q_u^{t-\tau_{uj}} + S_u^{t-\tau_{uj}}) \quad (11)$$

Where I_{hj}^t is water inflow rate of reservoir j at time interval t, S_{hj}^t is the spillage from reservoir j at time interval t, τ_{uj} is the water transport delay from reservoir u to reservoir j and R_{uj} is the number of upstream hydro reservoirs directly above the reservoir j.

8) Hydro Plant Power Generation Characteristic: The hydro power generation can be represented by the following equation:

$$P_{hj}^t = C_{1j}(V_{hj}^t)^2 + C_{2j}(q_{hj}^t)^2 + C_{3j}(V_{hj}^t)(q_{hj}^t) + C_{4j}(V_{hj}^t) + C_{5j}(q_{hj}^t) + C_{6j} \quad (12)$$

Where C_{1j} , C_{2j} , C_{3j} , C_{4j} , C_{5j} and C_{6j} are the Power generation coefficients of hydro generating unit j

III. Overview of ABC Algorithm

Artificial bee colony (ABC) is one of the most popular swarm intelligence algorithms for solving constrained and unconstrained optimization problems. It was first developed by Karaboga in 2005, inspired intelligent behaviors of real honey bee colonies [25]. The algorithm simulates the intelligent foraging behaviour of honey bees to achieve global optimum solutions for different optimization problems. The foraging behaviour of bees is to collect nectar from food sources around the hive in nature. In ABC algorithm, the position of food sources represents a possible candidate solution to the optimization problem, and the nectar amount of a food source corresponding to the profitability of associated solution. In ABC algorithm, the number of employed bees is equal to the number of food sources existing around the hive. If an employed bee could not improve the self solution in a certain time, it becomes a scout bee and the main purpose of which is to increase search ability of the ABC algorithm. The scout bees carry out a random search process for discovering new food sources. Compared to the other swarm based algorithms, the ABC algorithm has become very popular and it is widely used, because of its good convergence properties.

IV. Search Mechanism of ABC Algorithm

The colony of artificial bees consists of two groups of bees called employed bees and unemployed bees. The unemployed bees consist of onlookers and scouts. The main steps of the ABC algorithm are explained as follow:

1) Initialize a randomly food source positions by the following equation:

$$X_{ij} = X_j^{\min} + r \times (X_j^{\max} - X_j^{\min}) \quad (13)$$

$X_i = \{x_{i1}, x_{i2}, \dots, x_{iD}\}$, $i = 1, 2, \dots, N_s$, $j = 1, 2, \dots, D$ Where N_s is the number of food sources; D is the number of decision variables. r is uniformly distributed random value between $[0, 1]$, X_j^{\min} and X_j^{\max} are the lower and upper bounds of the decision variable j , respectively. After initialization, the population of the food sources (solutions) is subjected to repeated cycles of the search process of the employed bees, the onlooker bees and the scout bees. Then the fitness of each food source is calculated.

2) Each employed bee searches the neighborhood of its current food source to determine a new food source using Equation (14):

$$V_{ij} = X_{ij} + \phi_{ij} \times (X_{ij} - X_{kj}) \quad (14)$$

Where:

$k \in \{1, 2, \dots, N_s\}$, $j \in \{1, 2, \dots, D\}$ are randomly chosen indexes. It must be noted that k has to be different from i . ϕ_{ij} is a uniformly distributed real random number between $[-1, 1]$, it controls the production of neighbor food sources around X_{ij} and represents the comparison of two food positions visually by the bee.

If the new food source position produced by Equation (14) which exceeds their boundary values, it can be set as follow:

$$\text{If } X_i > X_i^{\max} \text{ then } X_i = X_i^{\max}$$

$$\text{If } X_i < X_i^{\min} \text{ then } X_i = X_i^{\min}$$

3) After generating the new food source, the nectar amount of food sources will be evaluated and a greedy selection will be performed. If the quality of the new food source is better than the current position, the employed bee leaves its current position and moves to the new food source, otherwise, the bee keeps the current position in the memory.

4) The onlooker bee chooses a food source by the nectar information shared by the employed bee, the probability of selecting the food source i is calculated by the following equation:

$$P_i = \frac{fit_i}{\sum_{j=1}^{NS} fit_j} \quad (15)$$

After selecting a food source, the onlooker generates a new food source by using equation (14). Once the new food source is generated it will be evaluated and a greedy selection will be applied same as the case of employed bees.

5) If the solution represented by a food source position cannot be enhanced for a predetermined number of trials (called limit), the food source is abandoned and the employed bee associated with that food source becomes a scout. The scout generates a new food source randomly using the following equation:

$$V_{ij} = X_j^{\min} + r \times (X_j^{\max} - X_j^{\min}) \quad (16)$$

Where $j \in \{1, 2, \dots, D\}$

6) If the termination criterion is satisfied (maximum number of cycles), the process is stopped and the best food source is reported; otherwise the algorithm returns to step 2.

The schematic diagram shows the mechanism search of ABC algorithm is illustrated in “Fig. 1”.

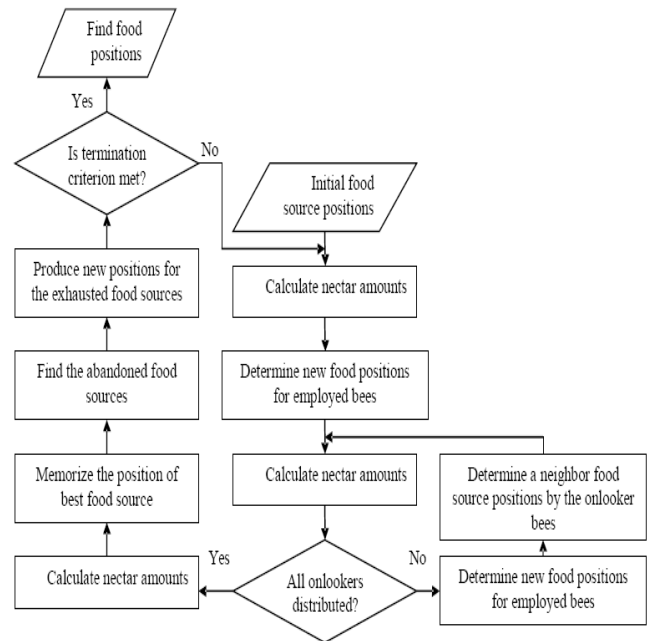


Figure 1: Schematic outline of ABC algorithm

V. ABC Optimization for Short term Hydrothermal Scheduling Problem

The artificial bee colony algorithm for solving short term hydrothermal scheduling problem is described as follow:

A. Construction of Solutions

In the initialization process, a set of food source positions are created at random. In this paper, the construction of solution for short term hydro thermal scheduling problem is composed of a set of elements which represent the water discharge rate of each reservoir and the power generation of thermal units over the whole scheduling period. Thus, the structure of solution is defined as follows:

$$X = \begin{bmatrix} q_{h1}^0 & q_{h2}^0 & \dots & q_{hj}^0 & P_{g1}^0 & P_{g2}^0 & \dots & P_{gi}^0 \\ q_{h1}^1 & q_{h2}^1 & \dots & q_{hj}^1 & P_{g1}^1 & P_{g2}^1 & \dots & P_{gi}^1 \\ M & M & O & M & M & M & O & M \\ q_{h1}^T & q_{h2}^T & \dots & q_{hj}^T & P_{g1}^T & P_{g2}^T & \dots & P_{gi}^T \end{bmatrix} \quad \text{--- (17)}$$

In the initialization process, the ABC algorithm generated the initial solutions by using the Equations (18) and (19) defined below.

$$P_{gi}^t = P_{gi}^{\min} + r_g \times (P_{gi}^{\max} - P_{gi}^{\min}) \quad (18)$$

$$q_{hj}^t = q_{hj}^{\min} + r_h \times (q_{hj}^{\max} - q_{hj}^{\min}) \quad (19)$$

Where r_g and r_h are uniformly distributed random real numbers in the range $[0, 1]$; $i = 1, 2, \dots, N$, $j = 1, 2, \dots, M$ and $t = 1, 2, \dots, T$

The feasible candidate solution of each element must be initialized within the feasible range.

The elements p_{gi}^t and p_{hj}^t are the output power generation of thermal unit i during the time interval t and the water discharge rate of hydro unit j at time interval t , respectively. The range of the elements p_{gi}^t and p_{hj}^t should satisfy the generating capacity limits of thermal generators and the water discharge rate constraints.

If any food source position is not satisfy the constraints, then the position of the food source is fixed to its minimum and maximum operating limits as follows:

$$P_{gi}^t = \begin{cases} P_{gi}^t & \text{if } P_{gi}^{\min} \leq P_{gi}^t \leq P_{gi}^{\max} \\ P_{gi}^{\min} & \text{if } P_{gi}^t \leq P_{gi}^{\min} \\ P_{gi}^{\max} & \text{if } P_{gi}^t \geq P_{gi}^{\max} \end{cases} \quad \text{----- (20)}$$

$$q_{hj}^t = \begin{cases} q_{hj}^t & \text{if } q_{hj}^{\min} \leq q_{hj}^t \leq q_{hj}^{\max} \\ q_{hj}^{\min} & \text{if } q_{hj}^t \leq q_{hj}^{\min} \\ q_{hj}^{\max} & \text{if } q_{hj}^t \geq q_{hj}^{\max} \end{cases} \quad \text{----- (21)}$$

$$V_{hj}^t = \begin{cases} V_{hj}^t & \text{if } V_{hj}^{\min} \leq V_{hj}^t \leq V_{hj}^{\max} \\ V_{hj}^{\min} & \text{if } V_{hj}^t \leq V_{hj}^{\min} \\ V_{hj}^{\max} & \text{if } V_{hj}^t \geq V_{hj}^{\max} \end{cases} \quad \text{----- (22)}$$

B. Evaluation of Fitness of Solutions:

Evaluate the fitness value of each food source position corresponding to the employed bees in the colony using the objective function described in Equation (1).

C. Modification of Food source positions by Employed Bees:

Each employed bee produces a new food source position by using equation (14). The modified position is then checked for constraints defined in Equations (5) and (8). If the new solutions violate the constraints, they are set

according to Equations (20) and (21). Then compute the fitness value of the new food source positions using Equation (1). The fitness of the modified position is compared with the fitness of the old position. If the new fitness is better than the old fitness, the employed bee memorized the new position and forgets the old one; otherwise, the employed bee keeps the old solution.

D. Sending the Onlooker Bees for Selected Positions and Evaluate Fitness:

Place the onlooker bees on the food sources with the nectar information shared by employed bees. Each onlooker bee chooses a food source based on the probability described in Equation (15). Onlooker bees search the new food sources in the neighborhood with the same method as employed bees.

E. Modification of Food Source Positions by Onlooker Bees:

The onlooker bees produce a modification on the position in its memory using Equation (14). Check the inequality constraints of the new positions. If the resulting value violates the constraint, they are set to the extreme limits. Then check the fitness of the candidate food source positions. If the new food source position is equal or better fitness than the old one, it replaces with the old one in the memory; otherwise, the old one is retained in the memory.

F. Abandon Sources Exploited by the Bees:

If the solution representing a food source is not improved by a certain number of trials, then that food source is abandoned and the employed bee will be changed into a scout. The scout randomly produces a new food solution by using Equations (18) and (19). Then, evaluate the fitness of the new solutions and compares it with the old one. If the new solution is better than the old solution, it is replaced with the old one. Otherwise, the old one is retained in the memory.

G. Check the Termination Criterion:

The proposed ABC algorithm is stopped if the cycle is equal to the maximum cycle number (MCN).

VI. Case Study and Simulation Results

The proposed algorithm has been tested on hydrothermal power system comprises of a multi chain cascade of four hydro units and three thermal units to verify the feasibility and effectiveness of the proposed ABC

algorithm. The effect of valve point loading has been taken into consideration to illustrate the robustness of the proposed method. The transport time delay between cascaded reservoirs is also considered in this case study. The scheduling time period is one day with 24 intervals of one hour each. The data of test system are taken from [16]. The configuration of multi chain hydro sub system is shown in “Fig. 2”. The water time transport delays between connected reservoirs are given in Table 1.

The hydro power generation coefficients are given in Table 2. The reservoir storage limits, discharge rate limits, initial and final reservoir storage volume conditions and the generation limits of hydro power plants are shown in Table 3. Table 4 shows the reservoir inflows of hydro power plants. The fuel cost coefficients and power output limits of thermal units are given in Table 5. The load demand over the 24 hours is given in Table 6. The control parameters of ABC algorithm are given in Table 7.

The optimal solution obtained from ABC algorithm is achieved in 50 trial runs. The optimal hourly hydrothermal generation schedule and hourly total fuel cost obtained by the ABC algorithm is shown in Table 8. Table 9 shows the optimal hourly water discharge of hydro power plants obtained from the ABC algorithm while Table 10 presents the optimal hourly storage volumes of hydro reservoirs obtained from the ABC algorithm.

The proposed algorithm has been implemented in MATLAB language and executed on an Intel Core i3, 2.27 GHz personal computer with a 3.0 GB of RAM.

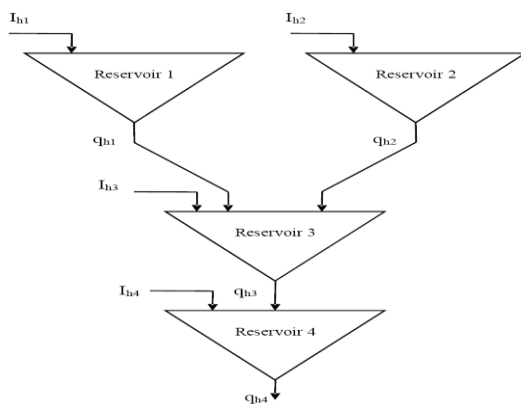


Figure 2: Multi chain hydro sub system networks

TABLE I
WATER TIME TRANSPORT DELAYS BETWEEN CONNECTED RESERVOIRS

Plant	1	2	3	4
R_u	0	0	2	1
τ_u	2	3	4	0

R_u : Number of upstream hydro power plants
 τ_u : Time delay to immediate downstream hydro power plant

TABLE II
HYDRO POWER GENERATION COEFFICIENTS

Plant	C_1	C_2	C_3	C_4	C_5	C_6
1	-0.0042	-0.4200	0.0300	0.9000	10.000	-50.000
2	-0.0040	-0.3000	0.0150	1.1400	9.5000	-70.000
3	-0.0016	-0.3000	0.0140	0.5500	5.5000	-40.000
4	-0.0030	-0.3100	0.0270	1.4400	14.000	-90.000

TABLE III
RESERVOIR STORAGE CAPACITY LIMITS, PLANT DISCHARGE LIMITS, PLANT GENERATION LIMITS AND RESERVOIR END CONDITIONS ($\times 10^4 m^3$)

Plant	V_h^{\min}	V_h^{\max}	V_h^{ini}	V_h^{end}	q_h^{\min}	q_h^{\max}	P_h^{\min}	P_h^{\max}
1	80	150	100	120	5	15	0	500
2	60	120	80	70	6	15	0	500
3	100	240	170	170	10	30	0	500
4	70	160	120	140	13	25	0	500

TABLE IV
RESERVOIR INFLOWS OF MULTI CHAIN HYDRO PLANTS ($\times 10^4 m^3$)

Hour	Reservoir				Hour	Reservoir			
	1	2	3	4		1	2	3	4
1	10	8	8.1	2.8	13	11	8	4	0
2	9	8	8.2	2.4	14	12	9	3	0
3	8	9	4	1.6	15	11	9	3	0
4	7	9	2	0	16	10	8	2	0
5	6	8	3	0	17	9	7	2	0
6	7	7	4	0	18	8	6	2	0
7	8	6	3	0	19	7	7	1	0
8	9	7	2	0	20	6	8	1	0
9	10	8	1	0	21	7	9	2	0
10	11	9	1	0	22	8	9	2	0
11	12	9	1	0	23	9	8	1	0
12	10	8	2	0	24	10	8	0	0

TABLE V
FUEL COST COEFFICIENTS AND OPERATING LIMITS OF THERMAL UNITS

Unit	a_i	b_i	c_i	e_i	f_i	P_{gi}^{\min}	P_{gi}^{\max}
1	0.0012	2.45	100	160	0.038	20	175
2	0.0010	2.32	120	180	0.037	40	300
3	0.0015	2.10	150	200	0.035	50	500

TABLE VIII
LOAD DEMAND FOR 24 HOUR

Hour	P _D (MW)	Hour	P _D (MW)	Hour	P _D (MW)	Hour	P _D (MW)
1	750	7	950	13	1110	19	1070
2	780	8	1010	14	1030	20	1050
3	700	9	1090	15	1010	21	910
4	650	10	1080	16	1060	22	860
5	670	11	1100	17	1050	23	850
6	800	12	1150	18	1120	24	800

TABLE VII
CONTROL PARAMETERS OF ABC ALGORITHM

ABC algorithm parameters	Value
Colony size (N _p)	50
Number of food sources (N _s)	25
Number of employed bees	25
Number of onlookers	25
Maximum cycle number (MCN)	300
Limit value	100

TABLE VIII
HOURLY OPTIMAL HYDROTHERMAL GENERATION SCHEDULE USING ABC ALGORITHM

Hour	Thermal generation (MW)			Hydro generation (MW)			
	P _{g1}	P _{g2}	P _{g3}	P _{h1}	P _{h2}	P _{h3}	P _{h4}
1	102.4411	181.2670	50.0000	73.5131	62.5056	53.8689	226.4043
2	22.1315	126.5600	174.2240	95.0352	55.7258	42.0007	264.3229
3	46.0797	133.2205	140.7144	55.6823	67.3702	00.0000	256.9329
4	20.0000	115.9043	86.1655	68.7149	82.1708	39.6308	237.4138
5	157.3638	40.0000	50.0000	90.1544	75.9778	00.0000	256.5040
6	112.1576	46.8703	226.4150	69.9569	58.6992	46.2835	239.6174
7	65.8606	209.7137	230.4331	52.1114	74.6900	47.6980	269.4933
8	129.3525	211.7074	231.0256	68.6976	46.2139	39.6663	283.3367
9	103.2970	210.0890	352.9299	59.5113	58.6124	51.4951	254.0652
10	103.8887	214.0891	311.2150	64.9068	65.5284	24.2415	296.1305
11	112.9518	212.7889	322.0855	85.1607	43.3682	53.4024	270.2423
12	102.2374	294.5060	324.2013	80.1515	39.6928	53.7267	255.4843
13	174.9917	289.5292	229.0650	89.3898	48.5825	49.0964	229.3454
14	101.1384	293.7887	212.6150	92.7409	43.7653	54.1977	231.7539
15	45.1796	210.6628	320.3588	96.1910	53.4461	53.8540	230.3078
16	127.0743	210.0301	319.3423	55.0720	64.9931	56.2501	227.2381
17	173.9267	208.9086	227.9670	85.5090	49.8735	56.3430	247.4722
18	172.0041	293.4674	229.1950	98.5474	39.9007	59.0776	227.8078
19	100.4064	207.9049	317.0150	81.9545	45.9833	40.7904	275.9455
20	175.0000	208.8229	229.0754	61.5574	46.8905	46.6797	281.9741
21	25.0439	210.1011	230.1837	74.5008	58.9527	54.8876	256.3302
22	76.0859	124.3536	229.2102	68.0906	52.6797	53.5424	256.0375
23	20.0000	147.0406	230.3625	99.3709	47.9393	58.6357	246.6510
24	103.3851	126.2126	140.6553	66.8475	50.1730	57.0228	255.7036

TABLE IX
HOURLY HYDRO PLANT DISCHARGE USING ABC ALGORITHM

Hour	Hydro plant discharges ($\times 10^4 \text{ m}^3/\text{hr}$)			
	Q _{h1}	Q _{h2}	Q _{h3}	Q _{h4}
1	7.6477	8.0963	16.3437	14.0836
2	12.8578	6.8962	19.2194	18.9513
3	5.3388	8.8177	25.6760	16.0064
4	6.9983	13.0735	15.8037	13.4801
5	11.5135	12.0182	24.9377	14.4783
6	7.4305	8.3711	11.4678	13.0000
7	5.0000	14.7109	10.5282	17.2684
8	7.0322	7.3416	18.0360	19.7492
9	5.7130	10.0189	14.4034	15.6409
10	6.2676	11.9777	21.8457	23.4767
11	9.1414	6.9553	12.6409	19.3910
12	8.2567	6.1849	13.7150	17.7008
13	9.7922	7.5317	17.0259	13.8451
14	10.3885	6.4754	15.3728	13.9507
15	11.1753	7.9140	16.0444	13.5071
16	5.0000	10.6610	14.7236	13.0000
17	8.8969	7.7224	15.3980	15.2572
18	11.6836	6.1585	13.4430	13.0000
19	8.4627	7.1085	20.9065	18.8872
20	5.7406	7.0701	19.3231	20.1202
21	7.3458	9.0879	16.7212	16.0635
22	6.4966	7.7739	17.5217	15.7994
23	12.0324	6.8722	14.9395	14.6374
24	6.3383	7.1300	15.7040	15.7211

TABLE X
HOURLY STORAGE VOLUME OF HYDRO RESERVOIRS USING ABC ALGORITHM

Hour	Reservoir storage volume ($\times 10^4 \text{ m}^3$)				Total fuel cost (\$/hr)
	V _{h1}	V _{h2}	V _{h3}	V _{h4}	
1	100.0000	80.0000	170.0000	120.0000	0
2	102.3523	79.9037	161.7563	125.0601	353.81
3	98.4945	81.0075	150.7369	127.7282	356.62
4	101.1557	81.1898	129.0609	138.9978	332.43
5	101.1574	77.1163	115.2572	141.3214	143.54
6	95.6439	73.0981	109.0635	151.7802	128.25
7	95.2134	71.7270	121.3497	148.7231	146.50
8	98.2132	63.0161	127.9780	141.9829	179.53
9	100.1812	62.6745	132.0138	140.2696	196.18
10	104.4682	60.6556	142.1421	139.0321	228.57
11	109.2006	60.0000	137.0980	137.4011	207.02
12	112.0592	62.0447	145.1680	130.6510	213.21
13	113.8025	63.8598	147.8268	126.6652	227.81
14	115.0103	64.3281	150.5328	129.8460	224.63
15	116.6218	66.8527	156.4053	131.2680	203.31
16	116.4465	67.9387	159.4576	133.8053	198.91
17	121.4464	65.2777	161.1756	135.5289	218.51
18	121.5496	64.5553	165.1015	135.6696	200.51
19	117.8660	64.3968	170.5224	136.1126	224.31
20	116.4033	64.2883	169.7052	138.1319	201.41
21	117.4127	65.8682	167.0431	137.3348	199.42
22	117.8669	66.7803	168.9412	137.9925	156.32
23	119.3703	68.0064	171.2616	139.7149	158.82
24	116.3383	69.1342	172.8933	140.0171	148.92
24	120.0000	70.0000	170.0000	140.0000	289.12

In order to verify and validate the effectiveness of the proposed algorithm, its simulation results will be compared with those obtained from the SA, EP, GA and CFPSO technique. Table 11 shows the comparison of total fuel cost and execution time of the proposed algorithm among other methods. From Table 11, it is clear that the ABC algorithm performs better than SA, EP, GA and CFPSO technique in terms of total fuel cost and execution time. "Fig. 3" shows the hourly thermal plant power generation by using proposed method, the hourly hydro plant power generation by using proposed algorithm is given in "Fig. 4", the hourly hydro plant discharges using ABC algorithm are shown in "Fig. 5" and "Fig. 6" presents the hourly reservoir storage volumes using proposed technique.

TABLE XI

COMPARISON OF TOTAL FUEL COST AND COMPUTATION TIME OF THE PROPOSED TECHNIQUE AMONG SA, EP, GA AND CFPSO METHODS

Method	Total fuel cost (\$)	CPU Time (Sec)
ABC	42909.009	79.16
SA [22]	45466.000	246.19
EP [22]	47306.000	9879.45
CFPSO [23]	44925.620	183.64
GA [23]	45392.009	198.57

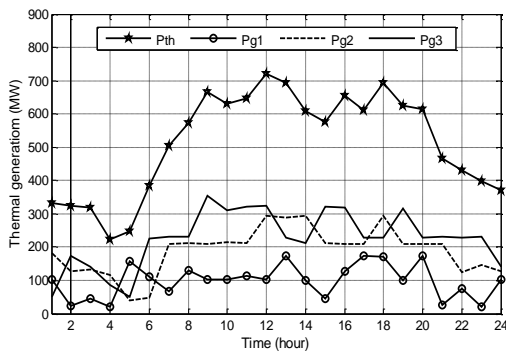


Figure 3: Hourly thermal plant power generation using ABC algorithm

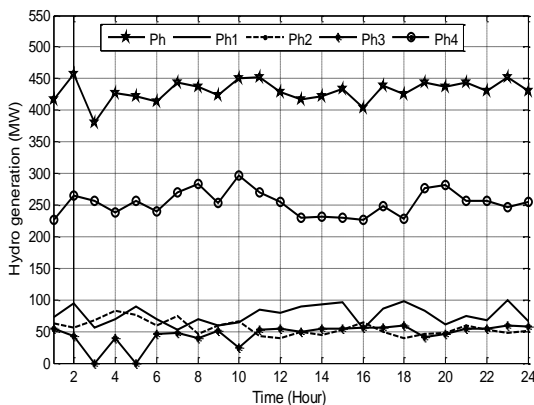


Figure 4: Hourly hydro plant power generation using ABC algorithm

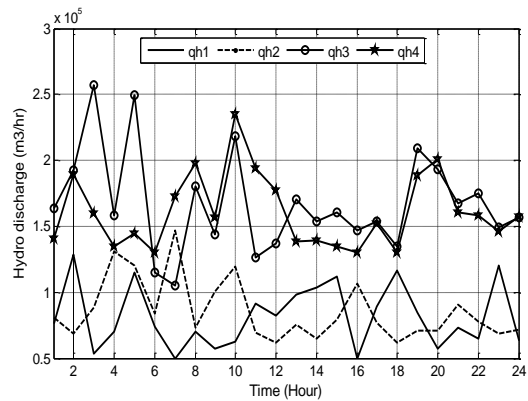


Figure 5: Hourly hydro plant discharges using ABC algorithm

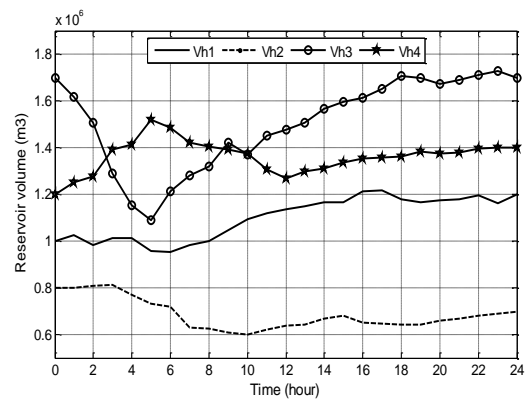


Figure 6: Hourly hydro reservoir storage volumes using ABC algorithm

VII. CONCLUSION

In this paper, an artificial bee colony (ABC) algorithm has been developed to solve the short term hydrothermal generation scheduling problem. To demonstrate the feasibility and performance efficiency of the proposed algorithm, a multi chain hydrothermal system was tested. The effect of valve point loading is considered in this case study to verify the robustness of the proposed technique. The numerical results indicate that the ABC algorithm can obtain better schedule results with minimum generation cost and lower execution time when compared with other evolutionary algorithms such as SA, EP, GA and CFPSO technique.

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