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# Solving Short Term Hydrothermal Generation Scheduling 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, two hydrothermal power systems were tested. The test system 1 consists of three thermal units and four cascaded hydro power plants. In this case study, the valve point loading effect is taken into consideration. The test system 2 consists of five thermal units and one pumped storage power plant. 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 total fuel cost saving and minimum execution time when compared to other methods.**

*Index Terms*— **Hydrothermal Generation Scheduling, Artificial Bee Colony, Valve Point Loading Effect**

## I. INTRODUCTION

The hydrothermal generation scheduling plays an important role in the operation and planning of a power system. The hydrothermal scheduling problem is a nonlinear programming problem including a nonlinear objective function and subjected to a mixture of linear and nonlinear operational constraints. Since the operating cost of hydroelectric 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 (typically one day) 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 [2-3]. Several mathematical optimization techniques have been used to solve short term hydrothermal scheduling problems [4]. In the past, hydrothermal scheduling problem is solved using classical mathematical optimization methods such as dynamic programming method [5-6], lagrangian relaxation method [7-8], mixed integer programming [9], interior point method [10], 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 [11-12], simulated annealing [13-15], differential evolution [16], artificial neural network [17-19], genetic algorithm [20 -23], particle swarm optimization [24-30], bacterial foraging algorithm [31-32] and artificial bee colony algorithm [33-36] 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 behavior 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:

$$FT=\sum_{t=1}^{T}\sum_{i=1}^{N} ntF_i^t(P_{gi}^t) \qquad (1)$$

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:

$$F_i^t(P_{gi}^t)=ai(P_{gi}^t)^2+biP_{gi}^t+ci \qquad (2)$$

Where $P_{gi}^t$ is the real output power of thermal generating unit i at time interval t in (MW), $F_i^t(P_{gi}^t)$ is the operating fuel cost of thermal unit i in ($/hr), $F_T$ is the total fuel cost of the system in ($), T is the total number of time intervals for the scheduling horizon, $n_t$ 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:

$$F_{i,v}^t(P_{gi}^t)=ai(P_{gi}^t)^2+biP_{gi}^t+ci+\left|ei\times\sin(fi\times(P_{gi}^{min}-P_{gi}^t))\right| \qquad (3)$$

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.

### Operational Constraints of Test System 1

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.

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

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:

$$P_{gi}^{min}\le P_{gi}^t\le P_{gi}^{max} \qquad (5)$$

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:

$$P_{hj}^{min}\le P_{hj}^t\le P_{hj}^{max} \qquad (6)$$

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:

$$V_{hj}^{min}\le V_{hj}^t\le V_{hj}^{max} \qquad (7)$$

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:

$$q_{hj}^{min} \le q_{hj}^{t} \le q_{hj}^{max} \qquad (8)$$

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.

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

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

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:

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

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, $\tau_{uj}$ 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:

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

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

## Operational Constraints of Test System 2

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

1) Active power balance constraint:

**i. In the generation mode:** 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.

$$\sum_{i=1}^{N} P_{gi}^{t} + \sum_{j=1}^{Mp} P_{j,g}^{t} = P_{D}^{t} + P_{L}^{t} \qquad (13)$$

**ii. In the pumping mode:** The pumped storage power plant consumes power from the electrical grid and the overall system load demand will be increased. The power balance equation becomes as follow:

$$\sum_{i=1}^{N} P_{gi}^{t} - \left| \sum_{j=1}^{Mp} P_{hj,p}^{t} \right| = P_{D}^{t} + P_{L}^{t} \qquad (14)$$

For simplicity, the transmission power loss is neglected in this paper.

Where, Mp is the total number of pumped storage power plants, $P_{hj,g}^{t}$ is the power generation of pumped storage plant j at time interval t in (MW) and $P_{hj,p}^{t}$ is the pumping power of the pumped storage plant j at time interval t in (MW).

2) Thermal generator limits constraint:

$$Pgi^{min} \le P_{gi}^{t} \le Pgi^{max} \qquad (15)$$

3) Pumped storage plant limits constraint:

**i. In the generation mode:**

The inequality constraint for the pumped storage plant in generation mode can be defined as:

$$P_{hj,g}^{min} \le P_{hj,g}^{t} \le P_{hj,g}^{max} \qquad (16)$$

Where $P_{hj,g}^{min}$ and $P_{hj,g}^{max}$ are the minimum and maximum power generation of pumped storage plant j in (MW), respectively.

**ii. In the pumping mode:**

The inequality constraint for the pumped storage plant in generation mode can be defined as:

$$P_{hj,p}^{min} \le P_{hj,p}^{t} \le P_{hj,p}^{max} \qquad (17)$$

Where $P_{hj,p}^{min}$ and $P_{hj,p}^{max}$ are the minimum and maximum power generation of pumped storage plant j in pumping mode, respectively.

4) Water discharge rate limit constraint:

$$q_{hj,g}^{min} \le q_{hj,g}^{t} \le q_{hj,g}^{max} \qquad (18)$$

Where $q^{t}_{hj,g}$ is the water discharge of pumped storage plant j at the time interval t, $q^{min}_{hj,g}$ and $q^{max}_{hj,g}$ are the minimum and maximum water discharge rate of pumped storage plant j, respectively.

5) Water pumping rate limit:

$$q^{min}_{hj,p} \le q^{t}_{hj,p} \le q^{max}_{hj,p} \qquad (19)$$

Where $q^{t}_{hj,p}$ is the water pumping of pumped storage plant j at the time interval t, $q^{min}_{hj,p}$ and $q^{max}_{hj,p}$ are the minimum and maximum water pumping rate of pumped storage plant j, respectively.

6) Reservoir storage volumes constraint:

$$V^{min}_{hj,u} \le V^{t}_{hj,u} \le V^{max}_{hj,u} \qquad (20)$$

$$V^{min}_{hj,L} \le V^{t}_{hj,L} \le V^{max}_{hj,L} \qquad (21)$$

Where $V^{t}_{hj,u}$ is the water volume of the upper reservoir of plant j at the end of time t, $V^{min}_{hj,u}$ and $V^{max}_{hj,u}$ are the minimum and maximum storage volume of upper reservoir of plant j, respectively; $V^{t}_{hj,L}$ is the water volume of the lower reservoir of plant j at the end of time t, $V^{min}_{hj,L}$ and $V^{max}_{hj,L}$ are the minimum and maximum storage volume of lower reservoir of plant j, respectively.

7) Water Dynamic Balance Constraint:

The water continuity equation relates the previous interval water storage in reservoirs with the current storage. The water continuity equation can be represented as:

$$V^{t}_{hj,u} = V^{t-1}_{hj,u} + I^{t}_{hj} - q^{t}_{hj,g} + q^{t}_{hj,p} - S^{t}_{hj} \qquad (22)$$

$$V^{t}_{hj,L} = V^{t-1}_{hj,L} + q^{t}_{hj,g} - q^{t}_{hj,p} + S^{t}_{hj} \qquad (23)$$

Where $I^{t}_{hj}$ is the water inflow rate into the upper reservoir of pumped storage plant j at time interval t and $s^{t}_{hj}$ is the water spillage from the upper reservoir of plant j at time interval t. for simplicity, the spillage is neglected in this paper.

8) Initial and Final Upper Reservoir Storage Volume Limit:

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

$$V^{0}_{hj} = V^{begin}_{hj} = V^{max}_{hj} \qquad (24)$$

$$V^{T}_{hj} = V^{end}_{hj} \qquad (25)$$

Where $V_{hj}{}^{begin}$ is the initial stored water volume in the upper reservoir of plant j and $V_{hj}{}^{end}$ is the final stored water volume in the upper reservoir of plant j.

For this case study, the starting and ending water reservoir volume of the pumped storage power plant are the same, thus, the total amount of water used for generation must be equal to the total amount of water pumped. Hence the total net water amount used by the pumped storage power plant must be zero.

$$q^{spent}_{tot} - q^{pump}_{tot} = q^{spent}_{net} = 0 \qquad (26)$$

$$q^{spent}_{tot} = \sum_{t=1}^{Tg} q^{t}_{hj,g} \times nt \qquad (27)$$

$$q^{pump}_{tot} = \sum_{t=1}^{Tp} q^{t}_{hj,p} \times nt \qquad (28)$$

Where $q^{spent}_{tot}$ is the total water amount which is spent for generation, $q^{pump}_{tot}$ is the total amount of pumped water, $q^{spent}_{net}$ is the total water amount used by the pumped storage plant during operation cycle, $T_g$ is sets which contains all time intervals where the pumped storage unit is operated in generation mode and $T_p$ is sets which contains all time intervals where the pumped storage plant is operated in pumping mode.

## 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 [33]. The algorithm simulates the intelligent foraging behavior of honey bees to achieve global optimum solutions for different optimization problems. The foraging behavior 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 [33]:

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

$$X_{ij}=X_j^{min}+r\times(X_j^{max}-X_j^{min}) \qquad (29)$$

$Xi=\{x_{i1}, x_{i2}, \ldots\ldots, x_{iD}\}$, $i = 1,2,\ldots, Ns$ , $j = 1,2,\ldots,D$

Where Ns 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 (30):

$$V_{ij}=X_{ij}+\phi_{ij}\times(X_{ij}-X_{kj}) \qquad (30)$$

Where: $k\in\{1,2\ldots\ldots,Ns\}$, $j\in\{1,2\ldots\ldots,D\}$ are randomly chosen indexes. It must be noted that k has to be different from i. $\phi_{ij}$ 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 (30) which exceeds their boundary values, it can be set as follow:

- If $X_i > X_i^{max}$ then $X_i = X_i^{max}$
- If $X_i < X_i^{min}$ 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:

$$P_i=\frac{fiti}{\sum_{j=1}^{NS} fitj} \qquad (31)$$

After selecting a food source, the onlooker generates a new food source by using equation (30). 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:

$$V_{ij}=X_j^{min}+r\times(X_j^{max}-X_j^{min}) \qquad (32)$$

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

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 Figure 1.

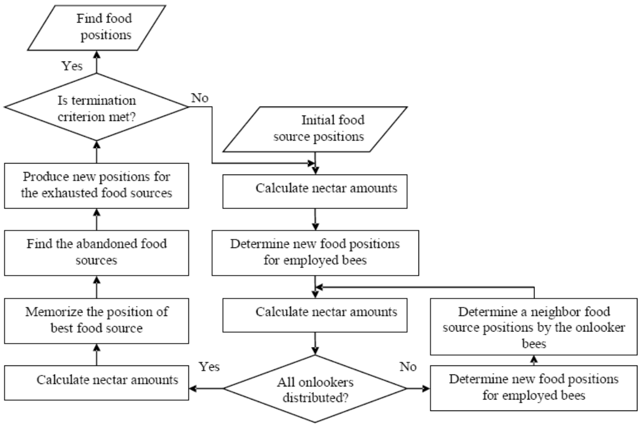

Fig.1 Schematic outline of ABC algorithm [34]

## VI. ABC OPTIMIZATION FOR SHORT TERM HYDROTHERMAL SCHEDULING PROBLEM

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

### 1) 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:

$$X = \begin{bmatrix} q_{h1}^{0} & q_{h2}^{0} & .....q_{hj}^{0} & P_{g1}^{0} & P_{g2}^{0} & .....P_{gi}^{0} \\ q_{h1}^{1} & q_{h2}^{1} & .....q_{hj}^{1} & P_{g1}^{1} & P_{g2}^{1} & .....P_{gi}^{1} \\ \vdots & \vdots\ \ddots & \vdots & \vdots & \vdots\ \ddots & \vdots \\ q_{h1}^{T} & q_{h2}^{T} & ....q_{hj}^{T} & P_{g1}^{T} & P_{g2}^{T} & .....P_{gi}^{T} \end{bmatrix} \qquad (33)$$

In the initialization process, the ABC algorithm generated the initial solutions by using the Equations (34) and (35) defined below.

$$P_{gi}^{t} = P_{gi}^{min} + r_g \times (P_{gi}^{max} - P_{gi}^{min}) \qquad (34)$$

$$q_{hj}^{t} = q_{hj}^{min} + r_h \times (q_{hj}^{max} - q_{hj}^{min}) \qquad (35)$$

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

$$P_{gi}^{t} = \begin{cases} P_{gi}^{t} & \text{if } P_{gi}^{min} \le P_{gi}^{t} \le P_{gi}^{max} \\ P_{gi}^{min} & \text{if } P_{gi}^{t} \le P_{gi}^{min} \\ P_{gi}^{max} & \text{if } P_{gi}^{t} \ge P_{gi}^{max} \end{cases} \qquad (36)$$

$$q_{hj}^{t} = \begin{cases} q_{hj}^{t} & \text{if } q_{hj}^{min} \le q_{hj}^{t} \le q_{hj}^{max} \\ q_{hj}^{min} & \text{if } q_{hj}^{t} \le q_{hj}^{min} \\ q_{hj}^{max} & \text{if } q_{hj}^{t} \ge q_{hj}^{max} \end{cases} \qquad (37)$$

$$V_{hj}^{t} = \begin{cases} V_{hj}^{t} & \text{if } V_{hj}^{min} \le V_{hj}^{t} \le V_{hj}^{max} \\ V_{hj}^{min} & \text{if } V_{hj}^{t} \le V_{hj}^{min} \\ V_{hj}^{max} & \text{if } V_{hj}^{t} \ge V_{hj}^{max} \end{cases} \qquad (38)$$

### 2) Evaluation of Fitness of Solutions:

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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).

### 3) Modification of Food source positions by Employed Bees:

Each employed bee produces a new food source position by using equation (30). 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 (36) and (37). 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.

### 4) 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 (31). Onlooker bees search the new food sources in the neighborhood with the same method as employed bees.

### 5) Modification of Food Source Positions by Onlooker Bees:

The onlooker bees produce a modification on the position in its memory using Equation (30). 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.

### 6) 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 (34) and (35). 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.

### 7) Check the Termination Criterion:

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

## VII. CASE STUDY AND SIMULATION RESULTS

Two hydrothermal power systems are tested to verify the feasibility and effectiveness of the proposed 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.

### Test System 1

This test system comprises of a multi chain cascade of four hydro units and three thermal units. 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 [19]. The configuration of multi chain hydro sub system is shown in figure 2. The water time transport delays between connected reservoirs are given in table I. The hydro power generation coefficients are given in table II. 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 III. Table IV shows the reservoir inflows of hydro power plants. The fuel cost coefficients and power output limits of thermal units are given in table V. The load demand over the 24 hours is given in table VI. The control parameters of ABC algorithm are given in table VII. 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 VIII. Table IX shows the optimal hourly water discharge of hydro power plants obtained from the ABC algorithm while table X presents the optimal hourly storage volumes of hydro reservoirs obtained from the ABC algorithm.

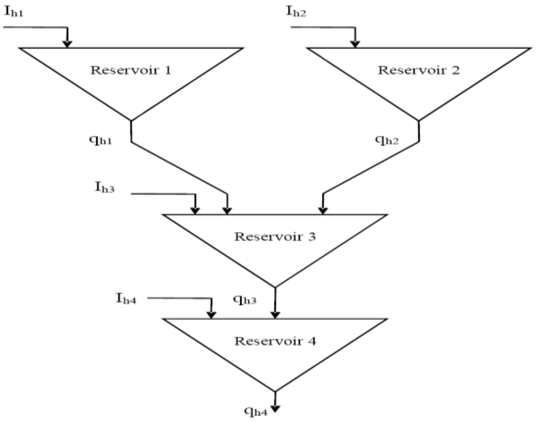

Fig.2 Multi chain hydro sub system networks

Table I Water time transport delays between connected reservoirs

| Plant | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $R_u$ | 0 | 0 | 2 | 1 |
| $\tau_u$ | 2 | 3 | 4 | 0 |

Ru : Number of upstream hydro power plants
τu : 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 | ai | bi | ci | $e_i$ | $f_i$ | $P_{gi}^{min}$ | $P_{gi}^{max}$ |
|---|---|---|---|---|---|---|---|
| 1 | 0.001 | 2.45 | 100 | 160 | 0.038 | 20 | 175 |
| 2 | 0.001 | 2.32 | 120 | 180 | 0.037 | 40 | 300 |
| 3 | 0.001 | 2.10 | 150 | 200 | 0.035 | 50 | 500 |

Table VI 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 (Np) | 50 |
| Number of food sources (Ns) | 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) | | | | Total fuel cost ($/hr) |
|---|---|---|---|---|---|---|---|---|
| | $P_{g1}$ | $P_{g2}$ | $P_{g3}$ | $P_{h1}$ | $P_{h2}$ | $P_{h3}$ | $P_{h4}$ | |
| 1 | 102.4411 | 181.2670 | 50.0000 | 73.5131 | 62.5056 | 53.8689 | 226.4043 | 1353.832 |
| 2 | 22.1315 | 126.5600 | 174.2240 | 95.0352 | 55.7258 | 42.0007 | 264.3229 | 1356.646 |
| 3 | 46.0797 | 133.2205 | 140.7144 | 55.6823 | 67.3702 | 00.0000 | 256.9329 | 1332.492 |
| 4 | 20.0000 | 115.9043 | 86.1655 | 68.7149 | 82.1708 | 39.6308 | 237.4138 | 1143.526 |
| 5 | 157.3638 | 40.0000 | 50.0000 | 90.1544 | 75.9778 | 00.0000 | 256.5040 | 1128.246 |
| 6 | 112.1576 | 46.8703 | 226.4150 | 69.9569 | 58.6992 | 46.2835 | 239.6174 | 1446.562 |
| 7 | 65.8606 | 209.7137 | 230.4331 | 52.1114 | 74.6900 | 47.6980 | 269.4933 | 1795.353 |
| 8 | 129.3525 | 211.7074 | 231.0256 | 68.6976 | 46.2139 | 39.6663 | 283.3367 | 1967.127 |
| 9 | 103.2970 | 210.0890 | 352.9299 | 59.5113 | 58.6124 | 51.4951 | 254.0652 | 2285.779 |
| 10 | 103.8887 | 214.0891 | 311.2150 | 64.9068 | 65.5284 | 24.2415 | 296.1305 | 2070.265 |
| 11 | 112.9518 | 212.7889 | 322.0855 | 85.1607 | 43.3682 | 53.4024 | 270.2423 | 2133.267 |
| 12 | 102.2374 | 294.5060 | 324.2013 | 80.1515 | 39.6928 | 53.7267 | 255.4843 | 2279.880 |
| 13 | 174.9917 | 289.5292 | 229.0650 | 89.3898 | 48.5825 | 49.0964 | 229.3454 | 2249.667 |
| 14 | 101.1384 | 293.7887 | 212.6150 | 92.7409 | 43.7653 | 54.1977 | 231.7539 | 2039.367 |
| 15 | 45.1796 | 210.6628 | 320.3588 | 96.1910 | 53.4461 | 53.8540 | 230.3078 | 1986.927 |
| 16 | 127.0743 | 210.0301 | 319.3423 | 55.0720 | 64.9931 | 56.2501 | 227.2381 | 2185.542 |
| 17 | 173.9267 | 208.9086 | 227.9670 | 85.5090 | 49.8735 | 56.3430 | 247.4722 | 2001.596 |
| 18 | 172.0041 | 293.4674 | 229.1950 | 98.5474 | 39.9007 | 59.0776 | 227.8078 | 2242.314 |
| 19 | 100.4064 | 207.9049 | 317.0150 | 81.9545 | 45.9833 | 40.7904 | 275.9455 | 2012.454 |
| 20 | 175.0000 | 208.8229 | 229.0754 | 61.5574 | 46.8905 | 46.6797 | 281.9741 | 1994.370 |
| 21 | 25.0439 | 210.1011 | 230.1837 | 74.5008 | 58.9527 | 54.8876 | 256.3302 | 1563.578 |
| 22 | 76.0859 | 124.3536 | 229.2102 | 68.0906 | 52.6797 | 53.5424 | 256.0375 | 1568.847 |
| 23 | 20.0000 | 147.0406 | 230.3625 | 99.3709 | 47.9393 | 58.6357 | 246.6510 | 1482.969 |
| 24 | 103.3851 | 126.2126 | 140.6553 | 66.8475 | 50.1730 | 57.0228 | 255.7036 | 1289.194 |

Table IX Hourly hydro plant discharge using ABC algorithm

| Hour | Hydro plant discharges ( $\times 10^4 m^3/hr$ ) | | | |
|---|---|---|---|---|
| | $q_{h1}$ | $q_{h2}$ | $q_{h3}$ | $q_{h4}$ |
| 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 ( $\times 10^4 m^3$ ) | | | |
|---|---|---|---|---|
| | $V_{h1}$ | $V_{h2}$ | $V_{h3}$ | $V_{h4}$ |
| 0 | 100.0000 | 80.0000 | 170.0000 | 120.0000 |
| 1 | 102.3523 | 79.9037 | 161.7563 | 125.0601 |
| 2 | 98.4945 | 81.0075 | 150.7369 | 127.7282 |
| 3 | 101.1557 | 81.1898 | 129.0609 | 138.9978 |
| 4 | 101.1574 | 77.1163 | 115.2572 | 141.3214 |
| 5 | 95.6439 | 73.0981 | 109.0635 | 151.7802 |
| 6 | 95.2134 | 71.7270 | 121.3497 | 148.7231 |
| 7 | 98.2132 | 63.0161 | 127.9780 | 141.9829 |
| 8 | 100.1812 | 62.6745 | 132.0138 | 140.2696 |
| 9 | 104.4682 | 60.6556 | 142.1421 | 139.0321 |
| 10 | 109.2006 | 60.0000 | 137.0980 | 137.4011 |
| 11 | 112.0592 | 62.0447 | 145.1680 | 130.6510 |
| 12 | 113.8025 | 63.8598 | 147.8268 | 126.6652 |
| 13 | 115.0103 | 64.3281 | 150.5328 | 129.8460 |
| 14 | 116.6218 | 66.8527 | 156.4053 | 131.2680 |
| 15 | 116.4465 | 67.9387 | 159.4576 | 133.8053 |
| 16 | 121.4464 | 65.2777 | 161.1756 | 135.5289 |
| 17 | 121.5496 | 64.5553 | 165.1015 | 135.6696 |

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| | | | | |
|---|---|---|---|---|
| 18 | 117.8660 | 64.3968 | 170.5224 | 136.1126 |
| 19 | 116.4033 | 64.2883 | 169.7052 | 138.1319 |
| 20 | 117.4127 | 65.8682 | 167.0431 | 137.3348 |
| 21 | 117.8669 | 66.7803 | 168.9412 | 137.9925 |
| 22 | 119.3703 | 68.0064 | 171.2616 | 139.7149 |
| 23 | 116.3383 | 69.1342 | 172.8933 | 140.0171 |
| 24 | 120.0000 | 70.0000 | 170.0000 | 140.0000 |

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 XI shows the comparison of total fuel cost and execution time of the proposed algorithm among other methods. From table XI, 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. Figure 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 figure 4, the hourly hydro plant discharges using ABC algorithm are shown in figure 5 and figure 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 [27] | 45466.000 | 246.19 |
| EP [27] | 47306.000 | 9879.45 |
| CFPSO [28] | 44925.620 | 183.64 |
| GA [28] | 45392.009 | 198.57 |

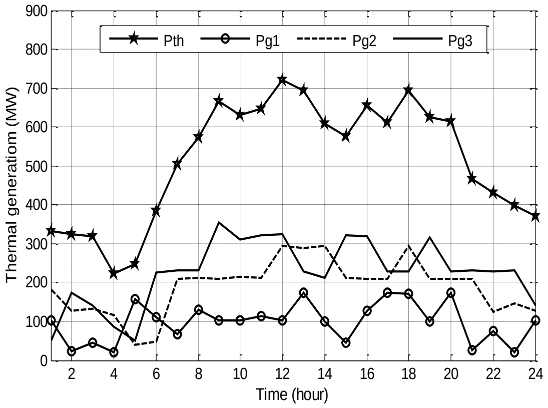

Fig.3 Hourly thermal plant power generation using ABC algorithm

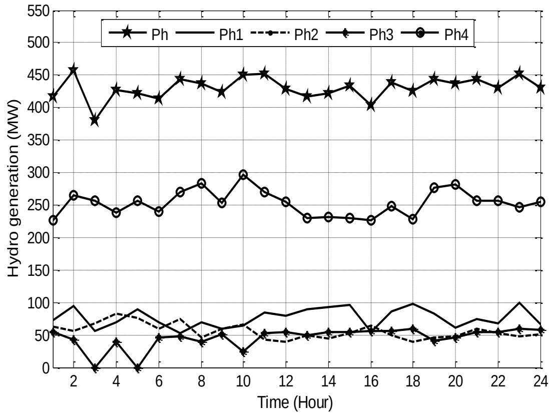

Fig.4 Hourly hydro plant power generation using ABC algorithm

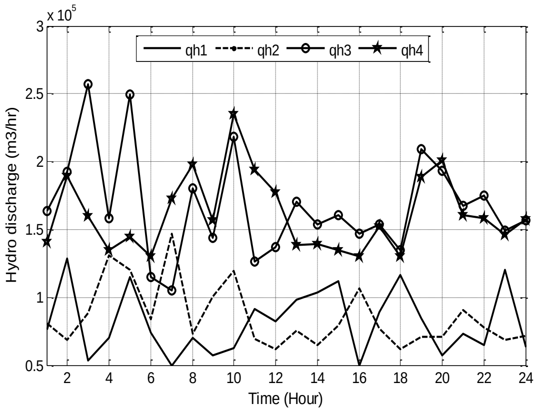

Fig.5 Hourly hydro plant discharges using ABC algorithm

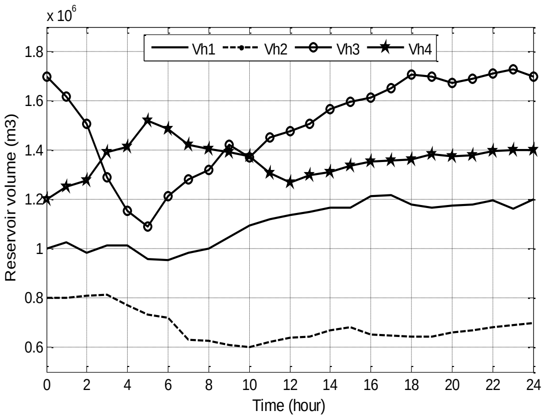

Fig.6 Hourly hydro reservoir storage volumes using ABC algorithm

### Test System 2

This test system consists of five thermal generating units and one pumped storage power plant. The single line diagram of the test power system is shown in figure 7. The data of test system are taken from [30]. The fuel cost data, the minimum and maximum limits of the thermal generating units are given in table XII. The reservoir storage limits, starting and ending water volumes and generation limits of the pumped storage power plant are given in table XIII. The water discharge rate of pumped storage unit is given in equation (39) and the water pumping rate of pumped storage unit is given in equation (40). The scheduling time period is one day with 24 intervals of one hour each. In this case study, the 24 hours operation cycle having six equal time intervals is considered. The load demand for the six time intervals is given in table XIV. The thermal units connected to buses 9 and 11 are chosen as inefficient units with respect to the other thermal units. So, these units are expensive and generate active power only in the time interval where the peak load demand occurs. The optimal control parameters used in ABC algorithm are listed in table XV. The program is run 50 times of ABC algorithm and the best among the 50 runs are taken as the final solutions. The test system is solved when the pumped storage plant is offline and is solved again when the pumped storage unit is online to determine the saving in fuel cost of thermal units. The resultant optimal schedule of thermal units obtained from the ABC algorithm when the pumped storage unit is offline is shown in table XVI. The fuel cost of each thermal unit and the total fuel cost of the thermal power system obtained from the ABC algorithm when the pumped storage plant is offline given in table XVII. The optimal schedules of pumped storage power plant and thermal units obtained from ABC approach is presented in table XVIII. The fuel cost of each thermal unit and total fuel cost over the day obtained from ABC algorithm when the pumped storage plant is online is given in table XIX. Table XIX presents the performance comparison between the ABC algorithm among other methods such as GA and CFPSO technique in terms of the cost saving and execution time.

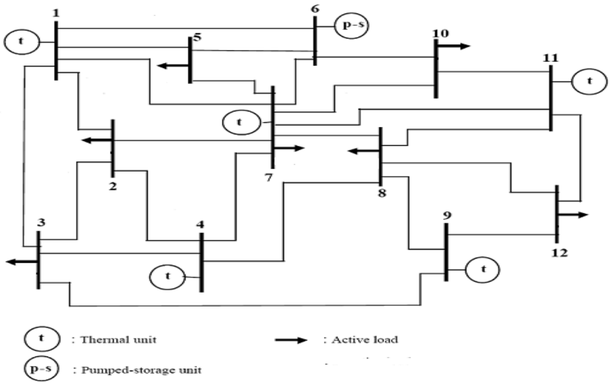

Fig.7 Single line diagram of the test power system

Table XII Fuel cost data of thermal generating power plants

| Plant | Bus | $a_i$ (\$/MW$^2$hr) | $b_i$ (\$/MWhr) | $c_i$ (\$/hr) | $P_{gi}^{min}$ (MW) | $P_{gi}^{max}$ (MW) |
|---|---|---|---|---|---|---|
| 1 | 1 | 0.001495 | 7.48 | 527 | 50 | 350 |
| 2 | 4 | 0.001562 | 7.92 | 561 | 45 | 180 |
| 3 | 7 | 0.001940 | 7.85 | 310 | 40 | 175 |
| 4 | 9 | 0.004360 | 9.52 | 476 | 5 | 100 |
| 5 | 11 | 0.003970 | 9.40 | 460 | 3 | 100 |

Table XIII Reservoir storage capacity limit, starting and ending water volumes and generation limits of pumped storage unit

| Plant | Bus | $V_h^{min}$ (acre-ft) | $V_h^{max}$ (acre-ft) | $V_h^{ini}$ (acre-ft) | $V_h^{end}$ (acre-ft) | $P_h^{min}$ (MW) | $P_h^{max}$ (MW) |
|---|---|---|---|---|---|---|---|
| 1 | 6 | 5000 | 15000 | 10000 | 10000 | 0 | 130 |

Table XIV Load demand for six time intervals

| Interval Number | Interval (Hour) | Load Demand (MW) |
|---|---|---|
| 1 | 00:00 – 04:00 | 200 |
| 2 | 04:00 – 08:00 | 600 |
| 3 | 08:00 – 12:00 | 800 |
| 4 | 12:00 – 16:00 | 600 |
| 5 | 16:00 – 20:00 | 300 |
| 6 | 20:00 – 24:00 | 200 |

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The water discharge rate curve of the pumped storage plant is given as follows:

$$q_{hg}\,(P_{hg}) = \begin{cases} 200+2.0\times P_{hg}\ \text{(acre-ft/hr)} & \text{if}\ \ 0 < P_{hg} \le 130\ \text{MW} \\ 0 \qquad\qquad\qquad\ \text{(acre-ft/hr)} & \text{if}\ \ \ P_{hg} = 0\ \text{MW} \end{cases} \tag{39}$$

The water pumping rate curve of the pumped storage plant is given as follows:

$$q_{hp}\,(|P_{hp}|) = \begin{cases} 200+\dfrac{4}{3}\times|P_{hp}|\ \text{(acre-ft/hr)} & \text{if}\ \ 0 < |P_{hp}| \le 130\ \text{MW} \\ 0 \qquad\qquad\qquad\quad \text{(acre-ft/hr)} & \text{if}\ \ \ |P_{hp}| = 0\ \text{MW} \end{cases} \tag{40}$$

Table XV Optimal generation schedule of thermal units obtained from ABC algorithm when pumped storage unit is offline

| Interval | $P_D$ (MW) | $P_1$ (MW) | $P_2$ (MW) | $P_3$ (MW) | $P_4$ (MW) | $P_5$ (MW) |
|---|---|---|---|---|---|---|
| 1 | 200.00 | 114.9984 | 45.0003 | 40.0013 | ---- | ---- |
| 2 | 600.00 | 306.5576 | 152.5637 | 140.8787 | ---- | ----- |
| 3 | 800.00 | 349.9998 | 180.0000 | 175.0000 | 39.1728 | 55.8274 |
| 4 | 600.00 | 306.5574 | 152.5619 | 140.8807 | ---- | ---- |
| 5 | 300.00 | 196.5758 | 47.2979 | 56.1263 | ---- | ---- |
| 6 | 200.00 | 114.9993 | 45.0001 | 40.0006 | ----- | ---- |

Table XVI Fuel cost of each thermal unit and total fuel cost obtained from ABC algorithm when pumped storage unit is online

| Interval | $F_1$ (\$/hr) | $F_2$ (\$/hr) | $F_3$ (\$/hr) | $F_4$ (\$/hr) | $F_5$ (\$/hr) | $F_T$ (\$/hr) | $F_T$ (four intervals) (\$/hr) |
|---|---|---|---|---|---|---|---|
| 1 | 1406.96 | 920.57 | 627.11 | ---- | ---- | 2954.64 | 11818.56 |
| 2 | 2960.55 | 1805.66 | 1454.40 | ---- | ---- | 6220.61 | 24882.44 |
| 3 | 3328.14 | 2037.21 | 1743.16 | 855.62 | 997.15 | 8961.27 | 35845.09 |
| 4 | 2960.55 | 1805.65 | 1454.42 | ---- | ---- | 6220.61 | 24882.44 |
| 5 | 2055.16 | 939.09 | 756.70 | ---- | ---- | 3750.95 | 15003.81 |
| 6 | 1406.97 | 920.56 | 627.10 | ---- | ---- | 2954.64 | 11818.55 |
| Total fuel cost over the day | | | | | | | 124250.9 |

Table XVII Optimal generation schedule of pumped storage plant and thermal units obtained from ABC algorithm

| Interval | $P_1$ (MW) | $P_2$ (MW) | $P_3$ (MW) | $P_4$ (MW) | $P_5$ (MW) | $P_s$ (MW) |
|---|---|---|---|---|---|---|
| 1 | 198.249 | 48.8992 | 57.4155 | ---- | ---- | 104.5641 |
| 2 | 294.037 | 140.567 | 131.220 | ---- | ----- | 34.1753 |
| 3 | 333.777 | 178.613 | 161.853 | ---- | ---- | 125.7565 |
| 4 | 294.324 | 140.847 | 131.443 | ---- | ---- | 33.3851 |
| 5 | 227.073 | 76.4806 | 79.6212 | ---- | ---- | -83.1754 |
| 6 | 197.391 | 48.0746 | 56.7483 | ----- | ---- | 102.2146 |

Table XVIII Fuel cost of each thermal unit and total fuel cost obtained from ABC algorithm when pumped storage unit is online

| Interval | $F_1$ (\$/hr) | $F_2$ (\$/hr) | $F_3$ (\$/hr) | $F_4$ (\$/hr) | $F_5$ (\$/hr) | $F_T$ (\$/hr) | $F_T$ (four intervals) (\$/hr) |
|---|---|---|---|---|---|---|---|
| 1 | 2068.664 | 952.017 | 767.107 | ---- | ---- | 3787.788 | 15151.151 |
| 2 | 2855.653 | 1705.159 | 1373.481 | ---- | ---- | 5934.293 | 23737.174 |
| 3 | 3190.206 | 2025.448 | 1631.370 | ---- | ---- | 6847.024 | 27388.095 |
| 4 | 2858.050 | 1707.497 | 1375.351 | ---- | ---- | 5940.898 | 23763.593 |
| 5 | 2302.596 | 1175.863 | 947.325 | ---- | ---- | 4425.784 | 17703.138 |
| 6 | 2061.740 | 945.361 | 761.722 | --- | ---- | 3768.823 | 15075.292 |
| Total fuel cost over the day | | | | | | | 122818.441 |

Table XIX Comparison of total fuel cost, cost saving and execution time of the proposed algorithm among GA and CFPSO methods

| Method | Thermal cost without pumped storage plant (\$) | Thermal cost with pumped storage plant (\$) | Cost saving (\$) | CPU time (second) |
|---|---|---|---|---|
| ABC | 124250.889 | 122818.441 | 1432.448 | 5.93 |
| CFPSO [29] | 124252.012 | 122880.251 | 1371.761 | 7.36 |
| GA [29] | 124255.853 | 122948.414 | 1307.439 | 13.21 |

## VIII. COMPARISON OF FUEL COST SAVING AND COMPUTATION TIME BETWEEN ABC ALGORITHM AND OTHER METHODS

The test results obtained when the pumped storage plant is offline are compared with those obtained when the pumped storage plant is online to determine the cost saving over the day. Cost saving is the thermal cost without pumped storage plant minus thermal cost with pumped storage plant.

The observations obtained from the test case study can be summarized as follows:

- **When the pumped storage plant is offline**

From the tabulated results, it is seen that the thermal units connected to buses 9 and 11 are expensive units and generate power only during the peak load time interval (time interval 3). The total fuel cost obtained from the ABC algorithm over the day was found to be \$124250.9.

- **When the pumped storage plant is online**

From the tabulated results it is seen that, the expansive thermal units connected to buses 9 and 11 are not operated during all time intervals. The simulation results obtained by ABC algorithm indicate that, the pumped storage power plant generates 773.2676 MWh during peak load periods and pumps up 1159.8164MWh during light load periods. The total thermal cost obtained from the ABC algorithm when the pumped storage unit is online is found to be \$122818.441, resulting in a cost saving of \$1432.448 in one day. The thermal cost curve converges to the optimal solution in 5.93 seconds. The amount of water stored at the end of the operation cycle is found to be 9999.8864 acre-ft/h. The load factor is improved from 0.563 to 0.692 due to the contribution of pumped storage unit. Figure 8 shows the generation/pumping schedules obtained using the ABC algorithm. The water discharge/pumping pattern of pumped storage plant using the ABC method is given in figure 9. Figure 10 gives the thermal cost without and with pumped storage power plant using the ABC approach. Figure 11 shows the thermal load profile without and with pumped storage plant using the proposed ABC algorithm.

From the tabulated results it is show that, the pumped storage power plant operates in pumping mode during the low load demand periods (i.e. time intervals 1, 5 and 6) and pumping power have higher value in time intervals 1 and 6 where the load demand is at its minimum value. The pumping storage power plant operates in generating mode during the peak load demand periods (i.e. time intervals 2, 3 and 4) and generate maximum power when the system load demand occurs (i.e. at time interval3). From table 19 it is observed that, the ABC give better cost saving and execution time than the GA and CFPSO technique.

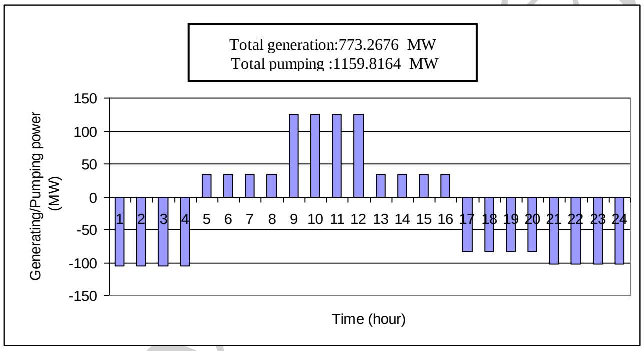

Fig.8 Generation/Pumping schedules using ABC algorithm

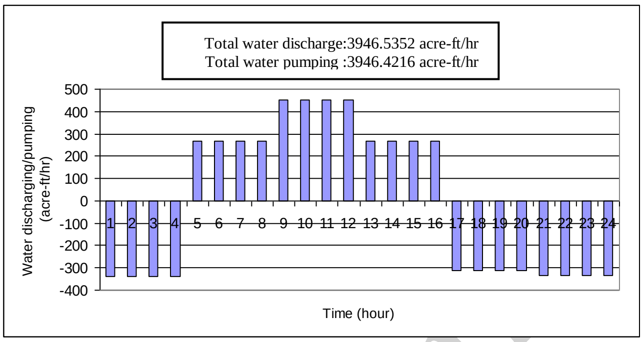

Fig.9 Water discharge/pumping pattern using ABC algorithm

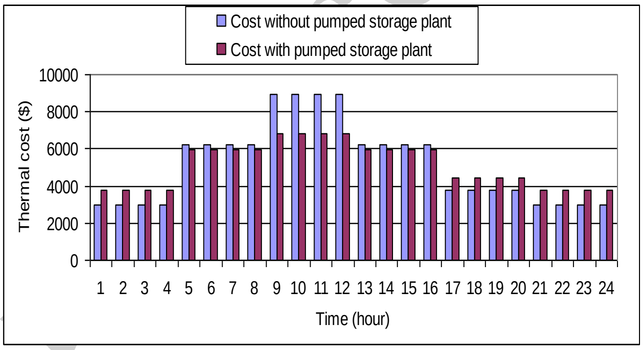

Fig.10 Total thermal cost using ABC algorithm

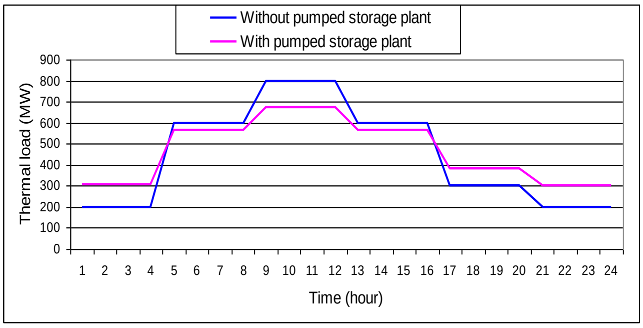

Fig.11 Thermal load profile using ABC algorithm

## VIX. CONCLUSIONS

In this paper, an artificial bee colony (ABC) algorithm has been developed to solve the short term hydrothermal scheduling problem. To demonstrate the feasibility and performance efficiency of the proposed algorithm, two cases were tested. In case study 1 the proposed algorithm was applied on multi chain cascade of four hydro power plants and three thermal plants. The effect of valve point loading is considered in this case study to verify the robustness of the proposed technique. In case study 2, the ABC algorithm has

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been implemented on hydrothermal system consists of five thermal units and one pumped storage power plant. In case study 1, 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. The ABC algorithm performs better than GA and CFPSO technique in terms of cost saving and computational time for case study 2. Due to the inclusion of pumped storage power plant, the load factor obtained by the proposed algorithm is improved from 0.563 to 0.692.

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