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Hybrid ABC-BAT for Solving Short-Term Hydrothermal Scheduling Problems

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Abstract: The main objective of short-term hydrothermal scheduling is the optimal allocation of the hydro and thermal generating units, so that the total cost of thermal plants can be minimized. The time of operation of the functioning units are considered to be 24 h. To achieve this objective, the hybrid algorithm combination of Artificial Bee Colony (ABC) and the BAT algorithm were applied. The swarming behavior of the algorithm searches the food source for which the objective function of the cost is to be considered; here, we have used two search algorithms, one to optimize the cost function, and another to improve the performance of the system. In the present work, the optimum scheduling of hydro and thermal units is proposed, where these units are acting as a relay unit. The short term hydrothermal scheduling problem was tested in a Chilean system, and confirmed by comparison with other hybrid techniques such as Artificial Bee Colony–Quantum Evolutionary and Artificial Bee Colony–Particle Swarm Optimization. The efficiency of the proposed hybrid algorithm is established by comparing it to these two hybrid algorithms.

Keywords: artificial bee colony; BAT algorithm; particle swarm optimization; quantum evolutionary; relay unit; short-term hydrothermal scheduling systems

1. Introduction

The optimal short-term hydrothermal scheduling (STHTS) problem is a challenging task in power systems. The primary target of this scheduling problem is to reduce the operating cost of thermal units over a certain time period (a day or a week) by satisfying various technical conditions [1]. A number of equality constraints determine the scheduling operation, including the power balance constraint, water availability constraints, and initial and final reservoir storage constraints. Here, the inequality constraints considered are hydro discharge constraints, generation constraints, and prohibited discharge zones [2]. Here, the problem considered is non-linear [3]. Therefore, the optimal scheduling of hydrothermal power system is more complex as it holds the nonlinear objective function and a fusion of equality and inequality constraints. Owing to its complexity, the hydrothermal scheduling (HTS) problem is partitioned into several tasks with different time periods, long-, medium-, and short-term problems, and each can be studied independently [4].

An important strategy for addressing STHTS is to implement optimal scheduling to utilize both the thermal and hydro power plants in a well-standardized manner. In this scheduling problem, the available water resources that are assigned to the hydro generator in each operational unit of time and the output power of thermal generators are determined, in order to reduce the total operating cost of satisfying the constraints of both the hydro and thermal units [5]. However, the initial cost of a thermal plant is low, but their working cost is especially high. On the other hand, though the working cost of a hydroelectric plant is high, their operating cost is low. With superior speed of reaction and advanced reliability, the hydroelectric plant is able to withstand oscillating loads [6]. Fixed head HTS and variable head HTS are the classifications of short period hydrothermal development. The hydro reservoirs that are present in the hydrothermal system are connected with each other in a hydraulic way, such that the downstream reservoirs consistently depend upon the upstream reservoirs.

Earlier papers have investigated the scheduling problem based on classical optimization techniques such as dynamic programming (DP) [7], nonlinear programming (NLP) [8], gradient search (GS) [9], network flow and linear programming (LP) [10], Newton's method [11], Lagrange relaxation (LR) [12], Lagrange multiplier method [13], and mixed integer programming (MIP) [14]. These techniques have resulting in scheduling problems; to address this, evolutionary algorithms have been used such as the Genetic Algorithm (GA) [15], meta heuristic simulated annealing (SA) [16], evolutionary programming (EP) [17], Hopfield neural network (HNN) [18], and quantum evolution (QE) [19]. However, the above-mentioned techniques have some drawbacks, such as high cost and poor performance, in solving short-term hydrothermal scheduling (STHTS) problems. Other related works are presented below.

The model of the transmission network was done at a high level of detail, and high level AC power flow was used to avoid post-dispatch corrections. These factors could be overcome by the novel decomposition approach proposed by Rubiales et al. [20]. Their approach combined generalized benders decomposition with bundle methods, and used the stabilized version of the cutting planes to reduce the tailing-off effect. It was decomposed using the quadratic mixed integer and non-linear problem. In each unit, active power separation was done and the reactive power was determined at a later stage to meet the electrical constraints through ideal AC power flow. Their proposed method was applied over the IEEE 24-bus and IEEE 9-bus test cases, and the problem was solved for a time limit of one hour.

When the medium-term horizon was compared with short-term forecasting, the volume of precipitation was accurately estimated by Dashti et al. [21]. Generation shortages and price spikes in a power system are triggered by the fluctuations of hydro resources. For hydrothermal power systems, the two stage robust scheduling method was developed. The water inflow uncertainty and the vector autoregressive model were taken to represent the seasonality and to construct the uncertainty set. These problems could be solved using the benders decomposition algorithm.

For generation and load demand of thermal plants, the uncertainties considered were the production cost, NOx, SO_2, and CO_2 emission, which caused the hydrothermal scheduling problem. In order to overcome these problems, non-dominated sorting Gravitational Search Algorithm (GSA) integrated with disruption operator (NSGSA-D) had been proposed by Nadakuditi et al. [22]. To adapt the non-sorting algorithm, the Pareto optimal solution was obtained. An external archive was used to store the Pareto optimal solutions. In order to speed up the convergence process and the search process, the disruption operator was exploited and the non-dominated solution was obtained by the policy of fuzzy decision making. The NSGSA-D approach gave a good quality solution and competitive performance for the multi objective short-term problem.

In power system economics, there was an issue like hydrothermal scheduling to optimize the hourly generation of output power for a variety of hydrothermal units in a certain interval of time to reduce the cost of generation. To solve the short-term hydrothermal scheduling problem, the new meta-heuristic technique was employed by Das et al. [23]. The symbiotic search algorithm was employed in three test systems, and the computational efficiency was computed. The relationship between two different species was defined by symbiosis, and the outcome of the symbiotic organisms search algorithm was compared with the performance of optimization techniques like evolutionary programming, genetic algorithm, differential evolution, and dynamic learning based particle swarm optimization.

In modern power systems, optimal short-term hydrothermal scheduling plays an important role in minimizing the total fuel cost of thermal units. Zhang et al. [24] used decomposition to divide the large population size to small population sizes, and subpopulations were developed by running a CPU process to find the optimal solution. The parallel DE method employed two different methods to avoid diversity of the small populations among different running processes. Four constraint handling rules were used to enhance the feasibility of the solution. The optimal solution for STHTS was generated by the numerical results, and the effectiveness of the DE algorithm was checked by IEEE 39-bus and IEEE 9-bus systems. The optimal scheduling for the fixed hydro units was defined by Basu [25]. The computation time was also calculated through the proposed approach, and a comparative analysis were carried out among particle swarm optimization, evolutionary programming, and differential evolution. The hydro thermal scheduling problem was identified by predator–prey based optimization, meaning that the thermal generating units could handle the power balance and the hydro units could estimate the water availability constraints that were established by Narang et al. [26]. Teaching and learning based optimization algorithm was applied by Roy [27], in which the test system was considered as a quadratic cost, analyzed with zones and without zones.

Elsaiah et al. [28] solved the economic power dispatch problem using a linear programming based method based on a linearized network model. They developed a piecewise linear model to handle different parameters. They tested their method using IEEE 300-bus systems.

These limitations have motivated us to focus on minimizing the total cost of hydrothermal power systems by scheduling of hydro and thermal units for a planned period.

The research objectives of this paper are: (i) optimal allocation of hydro and thermal units and (ii) cost reduction through the ABC-BAT algorithm.

The paper is arranged as follows. The problem formulation and proposed methodology for STHTS are discussed in Sections 2 and 3, respectively. The execution outcomes and detailed analysis are presented in Section 4. The conclusion is presented in Section 5.

2. Problem Formulation

The objective of the STHTS problem is to decrease the thermal generators for the entire fuel rate while fulfilling hydraulic, capacity balance, and generator operating limit restrictions, and other restrictions as discussed below. The mathematical formulation of mixed integer nonlinear programming (MINLP) is the hard problem. The installation cost of a thermal power plant is usually low when compared not only with a hydro plant, but also with all other power plants, but it has a high maintenance cost. The installation cost is high and running costs are low for a hydro power plant. At the same time, water availability for a hydro plant is a major issue when it is taken into consideration. Proper scheduling should yield constant electricity generation without any interruption. The thermal plant should be scheduled for the period during which water availability to the hydro system is at risk. Therefore, in hydrothermal development, minimization of cost comprises the best scheduling of the thermal plant, and suitable allocation of the hydro plant at different times.

The short-term hydrothermal scheduling problem has N_1 thermal elements and N_2 hydro elements with an M number of time intervals, and it is expressed by Equation (1). The main objective is to decrease the cost of thermal plants [25–27].

$$C_T = \min\left[\sum_{m=1}^{M}\sum_{i=1}^{N_1} t_m\left[a_{si} + b_{si}P_{si,m} + c_s P_{si,m}^2 + \left|d_{si} \times \sin\left(e_{si} \times \left(P_{si}^{\min} - P_{si,m}\right)\right)\right|\right]\right] \tag{1}$$

where a_{si}, b_{si}, c_{si}, d_{si} and e_{si}, represent the i^{th} thermal entity's value coefficients, $P_{si,m}$ is the i^{th} thermal unit's physical energy production at the m subinterval, $P_{si}^{\min}$ is the lower bound of P_{si} and t_m is the duration of subinterval m.

2.1. Equality Constraints

The equality constraints are as follows.

2.1.1. Power Balance Constraint

The energy from the thermal and hydro units with the power demand ($P_{D,m}$) and power loss ($P_{L,m}$) in every subinterval (m), ($P_{hj,m}$) is the power generated by j^{th} hydro unit at subinterval m, which is given in Equation (2).

$$\sum_{i=1}^{N_1} P_{si,m} + \sum_{j=1}^{N_2} P_{hj,m} - P_{L,m} - P_{D,m} = 0; \qquad m = 1, \ldots, M \tag{2}$$

Transmission loss is given by Equation (3) [25].

$$P_{L,m} = \sum_{i=1}^{N_1+N_2} \sum_{j=1}^{N_1+N_2} P_{i,m} B_{ij} P_{j,m} + \sum_{i=1}^{N_1+N_2} B_{0i} P_{i,m} + B_{00} \tag{3}$$

where B_{ij}, B_{00}, and B_{0i} are the loss coefficients and $P_{i,m}$ is the real power generation of the i^{th} unit during m^{th} interval.

2.1.2. Initial and Final Reservoir Storage Constraints

This equality condition is used to ensure full utilization of available water. This is indicated as expressed by Equation (4).

$$V_i^0 = V_i^{begin}, V_i^M = V_i^{end} \tag{4}$$

where V_i^{begin}, V_i^{end} are the initial and final storage volumes of the i^{th} reservoir.

2.1.3. Water Availability Constraint

The complete obtainable liquid released from every hydro plant for the total arranged period is restricted as expressed by Equation (5).

$$\sum_{m=1}^{M} t_m q_{j,m} = W_j; \qquad j = 1, \ldots, N_2 \tag{5}$$

where t_m is the duration of subinterval m, W_j is the water available in the j^{th} hydro unit, $q_{j,m}$ is the water flow at the m^{th} interval, and the cost of water movement from hydro plant j in interval m is evaluated by Equation (6).

$$q_{j,m} = a_{hj} + b_{hj} P_{hj,m} + c_j P_{hj,m}^2 \tag{6}$$

2.2. Inequality Constraints

2.2.1. Generator Operating Limits

Every thermal and hydro entity has their upper and lower production limits, which can be evaluated by Equations (7) and (8).

$$P_{si,\min} \le P_{si,m} \le P_{si,\max}; \qquad i = 1, \ldots, N_1; \qquad m = 1, \ldots, M \tag{7}$$

$$P_{hj,\min} \le P_{hj,m} \le P_{hj,\max}; \qquad j = 1, \ldots, N_2; \qquad m = 1, \ldots, M \tag{8}$$

2.2.2. Water Discharge Constraints

Hydro units may contain discharge zones, which are prohibited [27], and which can be expressed by Equation (9).

$$\begin{array}{l} q_i^{\min} \leq q_{i,m} \leq q_i^{LB,1} \\ q_i^{UB,n-1} \leq q_{i,m} \leq q_i^{LB,1} \qquad n = 2,3,\ldots\ldots,ND_i \\ q_i^{UB,n} \leq q_{i,m} \leq q_i^{\max} \qquad n = ND_i \end{array} \tag{9}$$

where $i = 1,2,3,4,\ldots\ldots,N_2$ and $m = 1,2,3,\ldots.M$, ND_i represent the prohibited released section of the i^{th} unit, and $q_i^{UB,n}$ and $q_i^{LB,1}$ are the upper and lower boundary reservoir discharge rates.

2.2.3. Reservoir Water Storage Limits

The maximum and minimum limits of the hydro power plant reservoir are given by Equation (10).

$$V_i^{\min} \leq V_i^m \leq V_i^{\max} \tag{10}$$

where $i = 1,2,3,\ldots.N_2$ and $m = 1,2,3,\ldots\ldots M$.

3. Modelling the ABC-BAT algorithm

STHTS is a key research problem in the field of power systems. After developing a suitable scheduling algorithm, one can reduce the cost required for the integration of hydroelectric and thermal power plants, and, at the same time, better performance can be attained. In this paper, the objective is to implement a hybrid algorithm in STHTS. The hybrid procedure involved uses artificial bee colony and bat optimization techniques, and is known as Hybrid ABC-BAT algorithm [29].

3.1. Computation of Output Power for Slack Thermal and Hydro Units

In this paper, the productivity control of moderate hydro elements was evaluated. This depends on the quality of liquid restriction, whereas the power production of thermal elements is computed by using the power plant generation. Assuming that the liquid released during the first *M*-1 subintervals of N_2 hydro elements is acquired, the liquid release for hydro element *j* at subinterval *m* is computed using the obtainable liquid restriction in Equation (5), as given in Equation (11).

$$q_{j,m} = \left(W_j - \sum_{\substack{k=1 \\ k \neq m}}^{M-1} t_k q_{j,k} \right) / t_m\,; \qquad j = 1,\ldots,N_2 \tag{11}$$

Therefore, the power production of hydro unit *j* at subinterval *m* is determined as given in Equation (12), using Equation (6).

$$P_{hj,m} = \frac{-b_{hj} \pm \sqrt{b_{hj}^2 - 4c_{hj}\left(a_{hj} - q_{j,m}\right)}}{2c_{hj}}; \qquad m = 1,\ldots,M; \qquad j = 1,\ldots,N_2 \tag{12}$$

Wherever $\left(b_{hj}^2 - 4c_{hj}\left(a_{hj} - q_{j,m}\right)\right) \geq 0$, the power generation represented by Equation (2) is always fulfilled and a moderated thermal element is randomly adopted. Therefore, its power production will be based on the power production of the remaining $N_1 - 1$ thermal sections and N_2 hydro sections in the system.

Let the outputs of $(N_1 - 1)$ thermal units as well as N_2 hydro units at subinterval *m* be known. The output power of the thermal unit 1, which is slack, is then computed by Equation (13).

$$P_{s1,m} = P_{D,m} - P_{L,m} - \sum_{i=2}^{N_1} P_{si,m} - \sum_{j=1}^{N_2} P_{hj,m} \tag{13}$$

Here, Equation (3) is modified in relation to the thermal unit 1 (slack) as given in Equation (14).

$$\begin{aligned} P_{L,m} &= B_{TT,11}P_{s1,m}^2 + \left(2\sum_{i=2}^{N_1} B_{TT,1i}P_{si,m} + 2\sum_{j=2}^{N_1} B_{TH,1j}P_{hj,m} + B_{T,01}\right)P_{s1,m} \\ &+ \sum_{i=2}^{N_1}\sum_{j=2}^{N_1} P_{si,m}B_{TT,ij}P_{sj,m} + \sum_{i=1}^{N_2}\sum_{j=1}^{N_2} P_{hi,m}B_{HH,ij}P_{hj,m} \\ &+ 2\sum_{i=2}^{N_1}\sum_{j=1}^{N_2} P_{si,m}B_{TH,ij}P_{hj,m} + \sum_{i=1}^{N_1} B_{T,0i}P_{si,m} + \sum_{j=1}^{N_2} B_{H,0j}P_{hj,m} + B_{00} \end{aligned} \tag{14}$$

where $B_{ij} = \begin{vmatrix} B_{TT,ij} & B_{TH,ij} \\ B_{HT,ij} & B_{HH,ij} \end{vmatrix}$ and $B_{0i} = \begin{vmatrix} B_{T,0i} \\ B_{H,0i} \end{vmatrix}$, $B_{TT,ij}$, $B_{T,0i}$ refer to power reduction constants of the thermal elements; $B_{HH,ij}$, $B_{H,0i}$ refer to power reduction constants of the hydro elements; $B_{TH,ij}$, $B_{HT,ij}$ refer to power reduction constants of the thermal and hydro elements, and $B_{TH,ij} = B_{HT,ij}^T$.

From Equation (13) and Equation (14) the following relationship is obtained.

$$A \times P_{s1,m}^2 + B \times P_{s1,m} + C = 0 \tag{15}$$

$$\text{Where} \qquad A = B_{TT,11} \tag{16}$$

$$B = 2\sum_{i=2}^{N_1} B_{TT,1i}P_{si,m} + 2\sum_{j=2}^{N_1} B_{TH,1j}P_{hj,m} + B_{T,01} - 1 \tag{17}$$

$$\begin{aligned} C = &\sum_{i=2}^{N_1}\sum_{j=2}^{N_1} P_{si,m}B_{TT,ij}P_{sj,m} + \sum_{i=1}^{N_2}\sum_{j=1}^{N_2} P_{hi,m}B_{HH,ij}P_{hj,m} \\ &+ 2\sum_{i=2}^{N_1}\sum_{j=1}^{N_2} P_{si,m}B_{TH,ij}P_{hj,m} + \sum_{i=1}^{N_1} B_{T,0i}P_{si,m} + \sum_{j=1}^{N_2} B_{H,0j}P_{hj,m} \\ &+ B_{00} + P_{D,m} - \sum_{i=2}^{N_1} P_{si,m} - \sum_{j=1}^{N_2} P_{hj,m} \end{aligned} \tag{18}$$

The solution of the second order Equation (15) is given in Equation (19).

$$P_{s1,m} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{19}$$

where $B^2 - 4AC \geq 0$.

3.2. Modeling STHTS Using ABC-BAT Technique

The hybrid algorithm is a combination of the ABC and BAT algorithms. The ABC algorithm is one of the best swarm intelligence optimization algorithms, which depends on the searching conduct of sugar bees for numerical optimization issues. In this paper, ABC was enforced to optimize the hydrothermal schedule constraints. Normally, ABC invariably contains three stages: the employed bee, onlooker bee, and scout bee. Here, the scout bee updating function was adapted in accordance with the bat-inspired algorithm, which functions mainly on the echolocation formation of the micro-bats. The micro-bats' echolocation constraints such as frequency, loudness, and pulse rate are the updating tasks that are utilized in the scout bee stage. Hence, this is defined as the hybrid ABC-BAT algorithm [29]. The optimal schedule for hydrothermal scheduling with the lowest price was obtained through the algorithm. Figure 1 shows the flowchart of STHTS using the hybrid ABC-BAT algorithm.

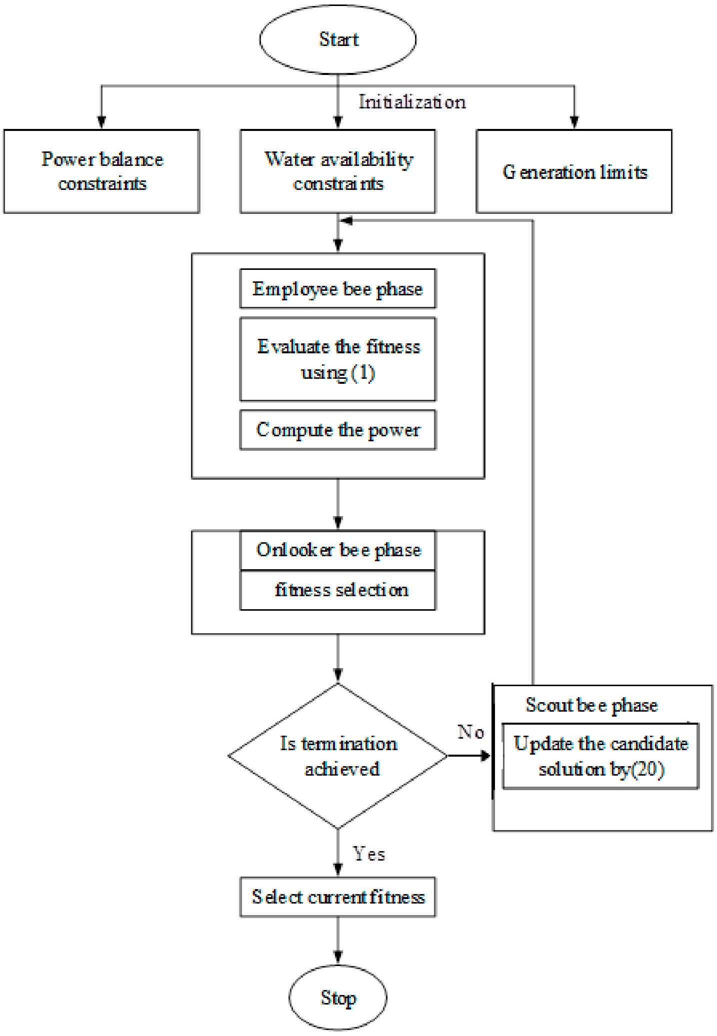

Figure 1. Flow chart of STHTS using proposed methodology.

Step 1: Representation of Candidate Solution

Every applicant resolution or food source is denoted by a binary matrix G_k containing the decision variables. A candidate solution is performed by each matrix, which must control all the data required to be transformed from another one. This is essential to find its fitness. The resolution variables are defined.

Every hydroelectric unit's power output is given for each hour. Table 1 [29] represents the creation levels, where every 3 bit association is applied indiscriminately. Solution G_k for each candidate then has an established of binary sub matrices H_k^j with size (3,$\boldsymbol{T}$) for the j^{th} hydro element. If any thermo-electric unit is controlled for an hour, its status will be 1. Otherwise, it will be 0. Formerly, every applicant answer G_k also covers an established of binary vectors E_k^j with length $\boldsymbol{T}$ for each thermo-electric unit, as shown in Figure 2 [29].

Table 1. Binary systematization example using 3 bit association.

%Phmaxj	0	40	50	60	70	80	90	100
Binary codification	0	0	0	0	1	1	1	1
	0	0	1	1	0	0	1	1
	0	1	0	1	0	1	0	1

Phmaxj: Max power generated in j^{th} hydraulic unit.

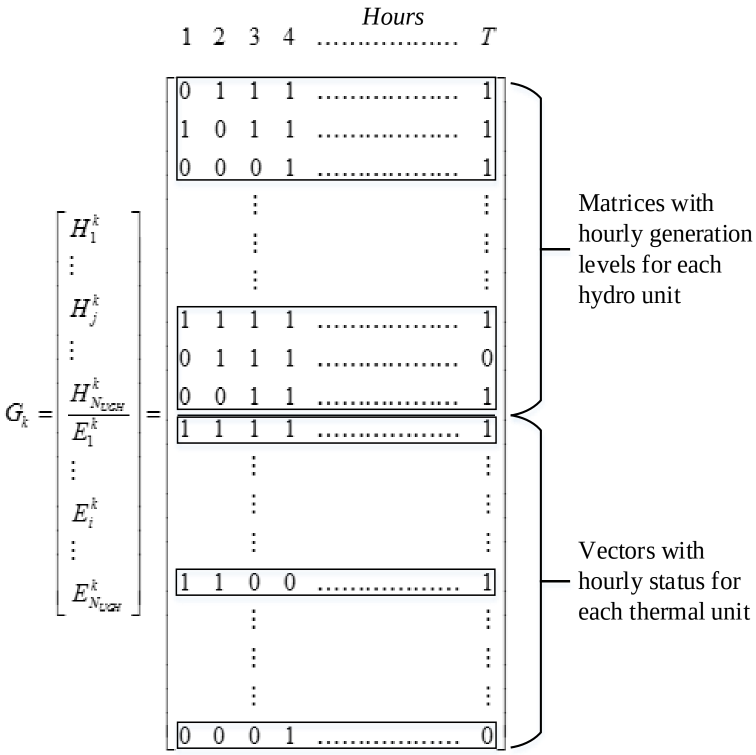

Figure 2. Candidate solution representation.

***Step 2:* Initialization**

The initial step of this algorithm is to set the input variables. The short-term hydrothermal scheduling problem involves optimal hourly releases of water from hydro reservoirs, to optimize the operating cost of thermal plant by considering several equality and inequality constraints, such as power balance constraints, water availability constraints, and generator operating limits. The population size used here was 100.

***Step 3:* Employee Bee Phase**

A comparison of various solutions was done in this phase. Evaluation of the capability (or cost) of every applicant infusion must be carried out. In order to achieve this, the strings were translated and the objective function, represented by Equation (1), for each applicant solution was calculated. The following steps are desired to be implemented in the solution of candidate to estimate their fitness.

Columns should be decrypted for each hydro sub-matrix H_k^j (*from* 1 to N_{UGH}), and computation of the terminal dimensions for every reservoir should be done. The fuel cost functions (FCFs) for the hydro group are then used to get the moment rate of hydro energy that is to be utilized during the week.

Hydro element generation is removed from the entire desired capacity demand, which is for each hour. An economic load dispatch is achieved to manage thermal units for each hour (obtained from vectors E_k^j). Lagrange multipliers are used to solve the economic load dispatch problem (ELDP). Thermal units are run at lowest possible cost to satisfy the thermal request, which is total minus hydro cost. Analyzing every one vector E_k^j, start-up and power failure costs are evaluated using Equation (20) [29]. The value of C_{sdi} is 0 for every thermal unit i, and C_{sui} is equivalent either to the cold begin cost ($C_{su\ \ cold\,i}$) or to the hot begin cost ($C_{su\ \ hot\,i}$), which depends on t_{down}. Here, t_{down} represents the down time of the unit.

$$C_{sui} = \begin{cases} C_{su,\,cold\,i},\ if\ t_{down} \leq T_{cold\,start\,i} \\ C_{su,\,hot\,i},\ if\ t_{down} > T_{cold\,start\,i} \end{cases} \tag{20}$$

Particular subroutines determine if each restriction is destroyed, and consequence aspects are computed.

Step 4: **Onlooker Bee Phase**

The purpose of the onlooker bee phase is to choose the best food sources (applicant resolution) for the required optimal schedule and to improve the applicant resolution. The onlooker bee phase receives the best solutions of lower price, and improves the speed of the populations using Equation (21).

$$V_{i,j} = x_{i,j} + \Phi_{i,j}(x_{i,j} - x_{k,j}) \tag{21}$$

where k is the key, the neighborhoods of i and Φ are an arbitrary amount within the limit $[-1, 1]$, and $V_{i,j}$ is the neighborhood result of $M_{i,j}$.

Step 5: **Selection**

The selection method is used to register the optimum fitness of the modified answers in calculation to resolve this probability. The probability task can be described by Equation (22).

$$\text{Probability} = \frac{\Phi}{\sum\limits_{i=1}^{n} \Phi} \tag{22}$$

Step 6: **BAT Optimization**

The BAT optimization is engaged for the optimal modification of the required candidate solution. The formula for updating the combination under the BAT inspired algorithm is given in Equation (23).

$$v_i^t = round\,[v_i^{t-1} + (X_i^{t-1} - X_\Psi)u_i] \tag{23}$$

where v_i^t and v_i^{t-1} represent the velocity vectors of the bees at the time steps t and $t-1$, X_i^t and X_i^{t-1} signify the position vectors of the bees at time steps t and $t-1$, and X_Ψ stands for the present global perfect solution. The specific search is then carried out in the discretely selected population, which is illustrated in Equation (24).

$$X_i^t = X_i^{t-1} + \xi_{i,j} l_{avg}^t \tag{24}$$

where $\xi_{i,j}$ represents a random number between -1 and 1, l_{avg}^t denotes the average value of loudness at time step t. These updated bees are included in the fitness Equation (1), and the fine fitness function is chosen as the optimal scheme with the lowest cost.

4. Results and Discussion

The proposed system for STHTS using the hybrid ABC-BAT process was implemented in the working platform of MATLAB (MathWords, Natick, MA, USA), with the system configuration of a Windows 8.1 operating system with 8 GB RAM and 3.19 GHz. Future cost function (FCF), which calculates the future cost of water of any hydro unit, has the input information from the reservoir inflows, and comprehensive data on hourly weight requests, water losses, current making elements, and primary constraints. To simultaneously handle the sub-problems of economic load dispatch, unit commitment, and short-term hydrothermal coordination, the abovementioned information was taken as input and processed. The scheduling was analysed at the week period. For the mentioned time period, the proposed method acquired hourly generation programs for each of the hydro and thermal units.

The unique case in short-term hydro generation scheduling problem (STHGSP) is the scheduling of a purely thermal system's generation. A schedule of 24 h for 5, 7, and 10 thermal unit schemes were considered [30], and the simulations were carried out. In the hydrothermal assessment scheme, a real model of the decreased number of demonstrative thermal units and, most importantly, six hydraulic reservoirs (and their connected hydraulic organizations) were incorporated. There were no time lags considered between units 7 and 8, except for a 2 h time lag. Here, six reservoirs were used, which comprised 11 hydro units and 10 thermal units. The hydraulic configuration of hydro units (a Chilean system), available in Reference [31], is considered here, and the related data of the Chilean system are also available in Reference [31]. Hourly demand for a weekday, Characteristics of reservoir and Characteristics of thermal units are available in [31].

The presentation of the suggested scheduling was analyzed by changing the number of thermal elements between 5, 7, and 10. The comparison parameters taken here were the cost and convergence.

The development of suitable and better scheduling techniques for short-term hydrothermal systems can be achieved through reduction of fuel rate, which is the main objective of the proposed method. Fulfilling the demand of the hydro units is enabled in an appropriate manner in the STHTS. The result obtained for the STHTS problem with the proposed system on weekdays is given in Table 2, and for Saturday and Sunday are given in Tables 3 and 4 respectively.

Table 2. Short-term hydrothermal scheduling outcome on weekdays.

Time (in hours)	Generated Volume (in MW)		Enabled Thermal Units (max 10)
	Hydro Units	Thermal Units	
1	990	1000	1 2 3
2	1300	700	1 2
3	840	1200	1 2 3 4
4	1170	1000	1 2 3
5	770	1350	1 2 3 4 5
6	990	1200	1 2 3 4
7	1170	1200	1 2 3 4
8	1350	1000	1 2 3
9	1040	1350	1 2 3 4 5
10	990	1350	1 2 3 4 5
11	1300	1200	1 2 3 4
12	1050	1350	1 2 3 4 5
13	1500	1000	1 2 3
14	990	1350	1 2 3 4 5
15	1200	1200	1 2 3 4
16	1170	1200	1 2 3 4
17	1400	1000	1 2 3
18	960	1500	1 2 3 4 5 6
19	1100	1350	1 2 3 4 5
20	1050	1500	1 2 3 4 5 6
21	840	1635	1 2 3 4 5 6 7 9
22	960	1350	1 2 3 4 5 10
23	1080	1000	1 2 3
24	1400	700	1 2

Table 3. Short-term hydrothermal scheduling outcome on Saturday.

Time (in hours)	Generated Volume (in MW)		Enabled Thermal Units (max 10)
	Hydro Units	Thermal Units	
1	1200	350	1
2	1200	350	1
3	980	700	1 2
4	990	700	1 2
5	980	700	1 2
6	840	1000	1 2 3
7	990	1000	1 2 3
8	1300	700	1 2
9	1080	1000	1 2 3
10	1200	700	1 2
11	1500	350	1 6
12	980	1000	1 2 3
13	1040	1000	1 2 3
14	1260	700	1 2
15	980	1000	1 2 3
16	770	1200	1 2 3 4
17	990	1000	1 2 3
18	840	1200	1 2 3 4
19	1500	700	1 2
20	1050	1000	1 2 3
21	1120	1000	1 2 3
22	1200	700	1 2
23	1100	700	1 2
24	910	700	1 2

Table 4. Short-term hydrothermal scheduling outcome on Sunday.

Time (hours)	Generated Volume (in MW)		Enabled Thermal Units (max 10)
	Hydro Units	Thermal Units	
1	1200	350	1
2	1200	350	1
3	980	350	1
4	990	700	1 2
5	980	700	1 2
6	840	700	1 2
7	990	700	1 2
8	1300	350	1
9	1080	700	1 2
10	1200	700	1 2
11	1500	350	1
12	980	700	1 2
13	1040	700	1 2
14	1260	350	1
15	980	700	1 2
16	770	1000	1 2 3
17	990	700	1 2
18	840	1000	1 2 3
19	1500	350	1
20	1050	700	1 2
21	1120	700	1 2
22	1200	700	1 2
23	1200	350	1
24	1200	350	1

The short-term thermal scheduling on a Saturday is given in Table 3, which shows the generation volume by the both hydro and thermal and corresponding thermal units in each hour. The computational time of the ABC-BAT, ABC-QE, and ABC-PSO was about 3.25, 6.08, and 11.68 s, respectively. The mathematical modeling provided in this section was derived using the working platform of MATLAB. This has an advantage over other tools, due to its lesser time consumption.

In Tables 3 and 4, the short-term hydrothermal scheduling outcomes on a Saturday and Sunday respectively are given. On weekends, the demand was reduced to 80% and 70% for Saturday and Sunday respectively, compared to week days. Hence, the number of thermal units needed is also reduced on weekends. The efficiency of the suggested system is then matched to approaches such as artificial bee colony–quantum evolutionary (ABC-QE) and artificial bee colony–particle swarm optimization (ABC-PSO) techniques. These algorithms were performed at 100 runs. In situations that are purely thermal and hydrothermal, the presentation of the proposed algorithm was matched. The presentation of the purely thermal system by various techniques is given in Table 5.

Table 5. Performance of purely thermal system.

Techniques	Performance	No. of Thermal Units		
		5	7	10
ABC-BAT	Variation	+60	+88	+50
	Cost ($)	122,691.37	122,695.49	122,720.32
ABC-QE	Variation	–76	–132	–228
	Cost ($)	122,693.26	122,712.90	122,753.40
ABC-PSO	Variation	+104	+100	+124
	Cost ($)	122,694.89	122,735.40	122,790.90

Table 5 shows the performance of purely thermal system scheduling by alternating hybrid techniques. The variation represents the difference between the generated and demand power. The variation must be a lower value (ideally it would be near zero). Otherwise, it can produce a range of power quality problems in the power system. By varying the number of thermal units, the performance was validated. Here, 5 thermal units, 7 thermal units, and 10 thermal units were considered as the three cases. The variation and total cost were the two parameters considered for the validation. Table 5 shows that the total cost required by the proposed technique is less than the other techniques. On the other hand, the variation by the proposed system was lower than the other methods, reflecting that the proposed technique almost satisfied the required power demand at a low price.

Table 6 shows the STHTS outcome by different techniques; the number of thermal units initialized by the proposed technique was less than the conventional techniques. Figure 3 shows the system demand, total hydro generation and total thermal generation.

Table 6. Performance of STHTS system.

Techniques	Generated Volume (in MW)		Enabled Thermal Units (max 10)	Total Cost (in $)
	Hydro Units	Thermal Units		
Proposed System	1300	700	1 2	122,592.03
ABC-QE	1300	900	1 2 3	122,595.24
ABC-PSO	1300	1250	1 2 3 4 5	122,630.20

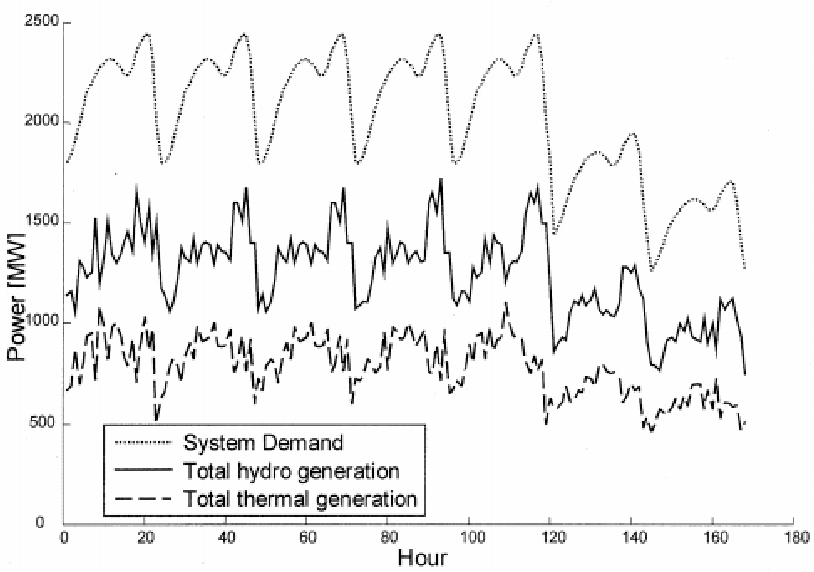

Figure 3. Thermal and hydro generation scheduled for a week.

Figure 4 shows the convergence of cost when the algorithm performed 100 iterations. As a result, the cost value was degraded, and the value is given in Table 6.

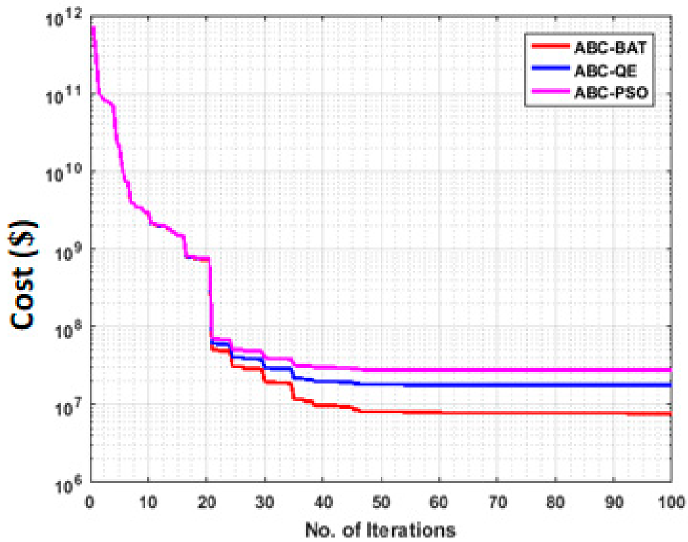

Figure 4. Convergence of cost.

5. Conclusions

STHTS is the most challenging task in integrating hydro and thermal units into the grid. The hydro generation units are used to balance the water availability, and the thermal power generation. So far, many techniques have been developed, in which short-term hydrothermal scheduling has been found to be difficult. Hence, the hybrid ABC-BAT algorithm is used in this paper. The results are varied with respect to the number of iterations and the fitness of the thermal generation units. The generation units and working hours used are mentioned. In a Chilean system, the proposed technique was tested under various situations. The outcomes obtained by the suggested method showed better performance than the other techniques for the considered problem in all situations. The proposed technique shows better results against hybrid ABC-QE and hybrid ABC-PSO algorithms. The total cost of ABC-BAT, ABC-QE, and ABC-PSO was about $122,592.03, $122,595.24, and $122,630.20, respectively.

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