Indian Journal of Science and Technology, *Vol 10(16), DOI: 10.17485/ijst/2017/v10i16/109055, April 2017*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Cost Effective Hydrothermal Scheduling with Practical Constraint using Artificial Bee Colony Algorithm

V. Moorthy[1*], P. Sangameswararaju[2] and Joseph Henry[3]

[1]Swarnandhra College of Engineering and Technology, Narsapur – 534280, Andhra Pradesh, India; moorthyv74@gmail.com
[2]S.V. University College of Engineering, Tirupati – 517502, Andhra Pradesh, India; raju_ps_2000@yahoo.com
[3]VelTech Dr. RR and Dr. University, Chennai – 600062, Tamil Nadu, India; joseph_henry@rediffmail.com

Abstract

Objective: Rapidly increasing economic development as well as energy consumption has raised great concern on resource-conservation. This focuses on finding cost effective dispatch to hydrothermal power systems. **Method/Approach:** The hydrothermal scheduling is formulated as a non-convex optimization problem subjected to the prohibited discharge zone of hydro reservoir, ramp rate limit of the thermal unit along with usual equality and inequality constraints. The Artificial Bee Colony algorithm is adopted as an optimization tool in which four different selection processes is employed that carry out exploration and exploitation process together in search space. **Findings:** The proposed methodology is implemented on the standard test system that comprises four cascaded hydro and three thermal units. As, hydro discharge and thermal real power generation are the decision variables a solution repair mechanism is adopted to handle water continuity and power balance constraints. Thus, the proposed ABC algorithm ascertains newfangled cost effective dispatch with practical constraint which is better than the previous reports in term of solution quality improvement. The proposed method seems to be a promising optimization tool for the utilities, thereby modifying their operating strategies to generate an electrical energy at minimum energy cost. Thus a strategic balance is derived among economic development, energy cost and environmental sustainability. **Originality/Improvements:** The system parameters are nicely incorporated in the proposed algorithm and strategic balance between exploration and exploitation is obtained perfectly. Hence, the ABC algorithm has converged fast and discovered best cost effective generation schedule. The effects of prohibited discharge zone and ramp rate limit are analyzed and also the values seem to be considered as practical value.

Keywords: Artificial Bee Colony, Cost Effective Dispatch, Hydrothermal Generation Schedule, Prohibited Discharge Zone, Ramp-Rate

1. Introduction

In the Hydrothermal Scheduling (HTS) problem cost effective dispatch is an imperative task that ascertains the optimal operation of the Hydrothermal Power System (HTPS) in such a way to minimize the total fuel cost of the thermal unit as the operational cost of hydroelectric plant seems to be insignificant[1]. The HTS is a combinatorial optimization problem as it includes non-convex objective function, nonlinear and non-smooth constraints, hence a suitable optimization tool is required to find the optimum solution. Numerous optimization tools have evolved in the past decades, which facilitate solving optimization problems that were previously difficult or impossible to solve. In which meta-heuristics optimization is one that deals with optimization problems using meta-heuristics algorithms. These are the simplest sense, gradient-free, non-deterministic, not problem specific and have been inspired by the natural selection process. Further, it can be classified into trajectory-based and population-based.

* Author for correspondence

The later one is preferred as it uses multiple agents which will interact and trace out multiple paths, whereas the earlier one uses a single agent and provide one solution at a time. Moreover, randomness features, intensification and diversification driving forces of the meta-heuristic algorithms bring the control parameters of the nonlinear problem to the edge, whereas, mathematical methods difficult to produce an accurate result. So, the meta-heuristic optimization is to be an effective tool to solve nonlinear problems[2].

In line for the solving HTS problem, the researchers have been successfully applied copious meta-heuristic algorithms and some of them are presented in this context. A Simulated-Annealing (SA) approach[3], Genetic Algorithm (GA)[4], an Evolutionary Programming (EP)[5], Particle Swarm Optimization (PSO)[6], Differential Evolution (DE)[7] approaches and cuckoo search algorithm[8] have proven their ability to solve the complex HTS problem. Afterwards, hybridization of two algorithms one that has global search ability and other holds local search behavior in the vicinity of finding the best solutions. Predominantly, Simulated Annealing-Genetic Algorithm (SA-GA)[9], Differential Evolution-Sequential Quadratic Programming (DE-SQP)[10], immune algorithm-PSO[11], has been enhanced the global search ability in continuous space for optimizing fuel cost in HTS problem.

Generally, the HTS problem as non-convex and non-linear, further the inclusion of Prohibited Discharge Zones of hydro plants and ramp rate limit of thermal plants increases the complexity of the problem. Therefore, the cuckoo search algorithm has applied for solving HTS problem with the hydraulic Prohibited Discharge Zone (PDZ)[12]. Meanwhile, Base has examined HTS problem with PDZ and ramp-rate limit of the thermal plant using Improved Differential Evolution (IDE)[13], Moreover, Malik et al. has exercised an improved chaotic hybrid differential evolution, including PDZ and ramp-rate limit of thermal plant (ICHDE)[14] whereas, Rasoulzadeh-akhijahani has implemented dynamic neighborhood learning based PSO for solving HTS with PDZ alone[15].

However, the reported optimization techniques had found optimum solution; it is not an end global solution to HTS problem due to the common shortcomings of algorithm complexity, premature convergence and large computational time. To overcome this drawback, a new emerging optimization tool, i.e., an Artificial Bee Colony (ABC) algorithm is preferred with suitable constraint handling strategy. After that, the superior convergence characteristics of the ABC algorithm than other swarm intelligence techniques, the performance of the ABC algorithm while solving a set of standard test functions[16,17] and the HTS problem[18] have been successfully analyzed.

As far as the state of the art, literature, there has been no attempt to verify the strategic balance between intensification and diversification of ABC algorithm in solving HTS problem with practical constraints. Hence, in this paper a preliminary investigation is attempting to explore the versatile characteristics of ABC algorithm viz. 1. Optimal values, 2. Feasible solution and 3. Solution quality.

The paper is organized into six sections, in the next section; mathematical formulation of HTS problem is briefed. Section 3 describes the ABC algorithm as an optimization tool, whereas; Section 4 deals implementation of an ABC algorithm for finding an optimal generation schedule. The numerical simulation results are presented and have compared in Section 5. Finally, the conclusion is presented in the last section.

2. Mathematical Formulation of HTS Problem

2.1 Objective Functions

As mentioned above hydropower production cost is insignificant, the main objective is to minimize the total fuel cost (F) of thermal plant and mathematically defined as:

$$Minimize\ F = \sum_{k=1}^{T}\sum_{i=1}^{N_s} t_k \left[f_{i,k}\left(P_{si,k}\right)\right] (\$) \tag{1}$$

Where,

$$f(P_{si,k}) = a_i + b_i P_{si,k} + c_i P_{si,k}^2 + \left| d_i \sin\left\{ g_i \left(P_{si}^{min} - P_{si,k} \right) \right\} \right|$$

$$(\$/MW-hr) \tag{2}$$

Where, a_i, b_i, c_i, e_i, f_i are coefficients of the cost curve and valve point effect of i^{th} thermal unit. T and t_k are generation duration and sub-interval time, N_s is number of thermal units and P_{sik} is its real power generation.

2.2 System Constraints

2.2.1 Power Balance

$$\sum_{i=1}^{N_s} P_{s,ik} + \sum_{j=1}^{N_h} P_{h,jk} - P_{D,k} - P_{L,k} = 0;\ k \in T \tag{3}$$

Where, N_h is number of hydro units and P_{hjk} is its real power generation. P_{Dk} and P_{Lk} are total power demand and network loss respectively. The hydroelectric generation is a function of water discharge rate and water storage volume. Mathematically,

$$P_{h,j} = C_{1j}V_{h,j}^2 + C_{2j}Q_{h,j}^2 + C_{3j}V_{h,j}Q_{h,j} + C_{4j}V_{h,j} + C_{5j}Q_{h,j} + C_{6j} \quad (4)$$

Where, $C_{1j}, C_{2j}, C_{3j}, C_{4j}, C_{5j}, C_{6j}$ are power generations coefficients of j^{th} hydro unit, V_{hj} and Q_{hj} are reservoir storage volume and discharge respectively.

2.2.2 Initial and Final Reservoir Storage

$$V_{h,jk}^{\ \ k=0} = V_{h,j}^{\ \ begin};\ V_{h,jk}^{\ \ k=T} = V_{h,j}^{\ \ end} \quad ;\ j \in N_h \quad (5)$$

2.2.3 Hydraulic Continuity

$$V_{h(j,k+1)} = V_{hj,k} + I_{hj,k} - Q_{hj,k} + \sum_{u=1}^{R_u}\sum_{k=1}^{T}\left[Q_{h(u,k-\tau)}\right] \quad (6)$$

Where, I_h, R_u and τ are natural inflow, number of upstream and water transport time delay to immediate downstream plant respectively.

2.2.4 Generation Limits

$$P_{hj}^{\min} \le P_{hj,k} \le P_{hj}^{\max};\ j = 1,2,....N_h \quad (7)$$

$$P_{si}^{\min} \le P_{si,k} \le P_{si}^{\max};\ i = 1,2,....N_s \quad (8)$$

Where, $P_{si}^{\min}$, $P_{si}^{\max}$ and $P_{hj}^{\min}, P_{hj}^{\max}$ are minimum and maximum power generation of thermal and hydro units respectively.

2.2.5 Reservoir Discharge

$$Q_{h,j}^{\min} \le Q_{hj,k} \le Q_{h,j}^{\max} \qquad j = 1,2,....N_h \quad (9)$$

Where, $Q_{hj}^{\min}$, $Q_{hj}^{\max}$ are minimum and maximum hydro discharges of j^{th} unit respectively.

2.2.6 Reservoir Storage Volume

$$V_{hj}^{\min} \le V_{hj,k} \le V_{hj}^{\max} \qquad j = 1,2.....N_h \quad (10)$$

Where, $V_{hj}^{\min}$, $V_{hj}^{\max}$ are minimum and maximum reservoir storage of j^{th} hydro unit respectively.

2.2.7 Prohibited Discharge Zones (PDZ)

Hydro plant may have certain Prohibited Discharge Zones where operation is either not desired or impossible due to physical limitations of the machine components or issues regarding instability. Hence, the following constraint for $Q_{hj,k}$ should be imposed[12].

$$\begin{cases} Q_{hj}^{\min} \le Q_{hj,k} \le Q_{hj,1}^{L} \\ Q_{hj,m-1}^{U} \le Q_{hj,k} \le Q_{hj,m}^{L} \ ;m = 2,3,..,ND_j \\ Q_{hj,m}^{U} \le Q_{hj,k} \le Q_{hj}^{\max} \quad ;m = ND_j \end{cases} \quad (11)$$

Where, Q_{hj}^{L}, Q_{hj}^{U} are lower and upper bound of the j^{th} prohibited discharge zone, ND is the number of the prohibited discharge zone.

2.2.8 Ramp Rate Limits of Thermal Plants

The power generated by the i^{th} thermal plant in a certain time interval should not exceed that of the previous time interval by more than a certain prescribed amount UR_i, the upper ramp limit, neither should it be less than that of the previous time interval by more than a certain defined amount DR_i, the down ramp limit of the i^{th} thermal plant. Mathematically, this constraint is formulated as[12]:

$$\begin{cases} P_{si,k} - P_{si,k-1} \le UR_i\ ;if\ generation\ increases \\ P_{si,k-1} - P_{si,k} \le DR_i\ ;if\ generation\ decreases \end{cases} \quad (12)$$

3. Overview of Artificial Bee Colony Algorithm

It is a bio-inspired swarm intelligent algorithm and developed by Karaboga by inspiring the intelligent foraging behavior of real honey bees. The colony of real honey bees consists of three groups; employed bees, onlooker bees and scout bee. The fascinating mechanism of honey bees used to perform during food foraging task was mathematically modeled as an Artificial Bee Colony (ABC) algorithm. It has been carried out in four phases with four selection process and few control parameters. The four different phases are:

- Initialization Phase
- Employed Bees Phase
- Onlooker Bees Phase
- Scout Bees Phase

In fact the ABC algorithm employs four different selection processes such as: A global probabilistic selection process is carried by the onlooker bees for discovering feasible search space. A local probabilistic selection process is carried by the employed and onlookers bees for determining a food source around the search space in the memory. A greedy selection process carried by an onlooker and employed bees, in which the prudent candidate source is memorized. A random selection process carried out by scouts.

3.1 Pseudo Code of ABC Algorithm

Step 1: Initialize the population of solutions using (13).

$$x_{k,l} = x_{k,l}^{\min} + rand\left[0,1\right]\left(x_{k,l}^{\max} - x_{k,l}^{\min}\right) \tag{13}$$

Where, $x_l^{\min}$, $x_l^{\max}$ are lower and upper boundaries in dimension "*l*", rand is a random number between [0 1].

Step 2: Population is evaluated.

Step 3: FOR cycle = 1; REPEAT

Step4: New solutions (food source positions) v_{kl} in the neighborhood of x_{kl} are produced for the employed bees using (14) is the solution in the i^{th} neighborhood, ϕ_{kl} being a random number ($-1 \le$ rand ≤ 1) and evaluate them.

$$v_{k,l} = x_{k,l} + \phi_{k,l}\left(x_{k,l} - x_{m,l}\right); k \ne m; m \in SP; l \in D \tag{14}$$

Step 5: Store the best values between x_{kl} and v_{kl} after greedy selection process.

Step 6: Probability values p_k for different solutions of x_k are calculated by means of their fitness values using (15). In this fit represents the fitness values of solutions and these are calculated using (15).

$$p_k = \frac{fit_k}{\sum_{m=1}^{SP} fit_m} \tag{15}$$

$$fit_k = \begin{cases} \dfrac{1}{1 + f\left(x_k\right)} & if\ f\left(x_k\right) \ge 0 \\ 1 + abs\left(f\left(x_k\right)\right) & if\ f\left(x_k\right) < 0 \end{cases} \tag{16}$$

Step 7: Based on probabilities (p_k), a new solution v_k for the onlooker is produced from x_k

Step 8: REPEAT Step-5

Step 9: Next, the abandoned solution is determined if exits and it is replaced with a newly produced random solution x_i for the scout as explained in scout bee phase i.e., using (13).

Step 10: Memorize the best food source obtained so far.

Step 11: Cycle = cycle+1

Step 12: UNTIL cycle = Maximum;

Step 13: STOP

4. Implementation of ABC for Solving HTS Problem

Application of an ABC algorithm to solve the environmental, economic hydrothermal generation schedule problem encompasses initialization, constraint handling and evaluation and metamorphoses. The step by step procedure of implementation can be summarized in this section.

Step 1: Initialization of trial vectors

There are two sets of trial vectors, one is hourly water discharge of hydro plant and another is the thermal generation denoting the current food set of the population to be evolved. These are randomly engendered within the operational limits based on (17) and (18).

$$Q_{h,jk} = Q_{hj}^{\min} + rand\left(Q_{hj}^{\max} - Q_{hj}^{\min}\right) \tag{17}$$

$$P_{s,ik} = P_{si}^{\min} + rand\left(P_{si}^{\max} - P_{si}^{\min}\right) \tag{18}$$

Considering Prohibited Discharge Zones (PDZs) of hydro plant, the discharge rate may lie in prohibited regions i.e. $\left(Q_{hj}^{L} < Q_{hj,k} < Q_{hj}^{U}\right)$ [15]. So as to expel the food from PDZs, a constraint for discharge rate represented by (11) should be imposed. Unlike thermal generation the hourly hydro discharge should be satisfied hydraulic dynamic constraints, initial and final reservoir volume constraints. In order to handle above mentioned constrains a solution repair mechanism is adopted in the algorithm. Therefore, a dependent interval "d" was chosen randomly and discharge at that interval was calculated by re-arranging (6) and given by (19), until (7) is satisfied otherwise hydrogenation was computed using (4) with an available storage volume of water and satisfied water discharge.

$$Q_{hj\,d} = V_{hj}^{begin} - V_{hj}^{end} - \sum_{\substack{k=1 \\ k \ne d}}^{T} Q_{hj,k} + \sum_{k=1}^{T} I_{hj,k} + \sum_{u=1}^{R_u} \sum_{k=1}^{T} Q_{h(u,j} \tag{19}$$

Then, the set of trial a vector is structured as an array to fix the position of initial solution [SP x T* (N_h+N_s)] and are deployed for entire schedule horizon to obtain an optimum generation schedule.

$$x^o = \left[Q_{h11} \ldots Q_{h1T} \ldots Q_{hj1} \ldots Q_{hjT}\ P_{s11} \ldots P_{s1T} \ldots\ P_{si1} \ldots P_{siT}\right] \tag{20}$$

Step 2: Fitness Evaluation of Augmented Objective Function

An Augmented Objective Function (AOF) is derived using (21), which is the sum of the objective function considered and absolute value in violation of power balance constraint with a high valued scalar multiplier. This technique converts the primal constrained problem into an unconstrained problem.

$$AOF = \left(objective + 1000 * \left| \sum_{k=1}^{T} \sum_{m=1}^{N_s+N_h} \left(P_{m,k} - P_{Dk} - P_{Lk} \right) \right| \right) \tag{21}$$

The fitness value of all individuals of the current food set matrix (x^o) is calculated using (22), the best one is identified and stored in a memory location for the next phase.

$$fit_i = \begin{cases} \dfrac{1}{1+AOF} & if\ AOF \geq 0 \\ 1+abs\left(AOF\right) & if\ AOF < 0 \end{cases} \tag{22}$$

Step 3: Updating Food Position for Optimal Solution

The new position of each food source, if $Q_{hj,k}$ and $P_{si,k}$ violate their allowable ranges and they are limited to their respective ranges.

$$x_i^{',new} = x_i^{new} + rand[0\ 1] * \left(x_i^{new} - x_i^{old} \right); i \in \left(N_s + N_h \right) \tag{23}$$

Likewise, the fitness value of all individuals of the updated food set matrix is calculated using (15), the best one is identified and stored in a memory location for the next phase. Then the step 3 is repeated for next phase and followed **step 2** is performed to identify the best solution.

Step 4: Fitness Evaluation of the New Food Source Position

For the new position of each control variable, the AOF is calculated as described in the steps 2. Then, the best food source is memorized and unimproved food sources are abandoned by scout bee.

Step 5: Modification of Thermal Generation Schedule

Since the hydro generation is computed from optimum water discharge and satisfied storage volume the modification of hydro power can affect the previous water discharge. Hence, all hydro and first N_s-1 thermal generations are retained at the optimum value and one thermal generation is modified to satisfy the power balance equation based on solution repair strategy. It can be solved using standard algebraic method and the positive root is chosen as the generation of the slack thermal unit that satisfies the equality constraint (3) perfectly.

$$B_{dd} P_{sd,k}^2 + \left(2 \sum_{m=1}^{(N_s+N_h)-1} B_{d,m} P_{m,k} - 1 \right) P_{sd,k} + \left(\sum_{m=1}^{(N_s+N_h)-1} \sum_{n}^{(N_s+N_h)-1} P_{m,k} B_{mn} P_{n,k} + \sum_{m=1}^{(N_s+N_h)-1} B_{m,0} P_{m,k} - \sum_{\substack{m=1 \\ m \neq d}}^{(N_s+N_h)-1} P_{m,k} + B_{00} + P_{Dk} \right) = 0; k \in T \tag{24}$$

Step 6: Inequality Constraints Handling Mechanism

The decision variables of hydro plant discharge and thermal plant output power are kept in the valid range by handling appropriately. Generally, the hydro discharge will be handled using (9). Considering Prohibited Discharge Zones (PDZs) of hydro plants the discharge rate may be handled as follows[15]:

$$Q_{hj,k} = \begin{cases} Q_{hj,m}^{L} & rand \leq 0.5 \\ Q_{hj,m}^{U} & rand > 0.5 \end{cases} \quad m = 2,3,..ND_j \tag{25}$$

The ramp rate limits of i^{th} thermal generating unit can be described by (12) and is combined with the inequality (8) and then operating limits of thermal units can be handled as follows[15]:

$$\left. \begin{aligned} P_{si,k}^{r\max} &= \min\left\{ P_{si}^{m\mathrm{ax}}, \left(P_{si,k-1} + UR_i \right) \right\} \\ P_{si,k}^{r\min} &= \max\left\{ P_{si}^{\min}, \left(P_{si,k-1} - DR_i \right) \right\} \\ P_{si,k}^{r\min} &\leq P_{si,k} \leq P_{si,k}^{r\max} \end{aligned} \right\} \tag{26}$$

Step 7: Evaluation of the Stopping Condition

If $iter \leq \max Cycle$, go to step 3. Otherwise, the ABC algorithm terminates.

5. Simulation Results and Discussion

The practical constraints of PDZ[15] on the hydro reservoir discharge and the ramp-rate limit[15] of thermal plants are included in the test system. It consists of a cascaded four hydro plants and three thermal plants, whose total scheduling period is 24 hours with an hour interval for each scheduling period[4]. The ABC algorithm is developed in the MATLAB 7.9 platform and is executed on an Intel (R) Core (TM) i5-4210C CPU, 1.70GHz, 4-GB RAM computer.

5.1 Optimal Solution

The simulation is carried for minimizing non-convex quadratic fuel cost of the thermal unit in coordination with hydro plant. Therefore, the hydro discharge is optimized using an ABC algorithm over a 200 independent iteration with same control variables in conjunction with thermal plant real power generation. The optimum hourly hydro reservoir discharge to minimum fuel cost has been presented in Table 1. It is observed that the discharges are optimized within the operating limits and also the discharge lie in between PDZ is expelled into either below the lower limit or above the upper limit of PDZ. i.e. the discharge at intervals-5, 19, 21 and 22 of reservoir-1, intervals-1, 3, 6, 10, 11, 12, 15, 16, 19 and 24 of reservoir-2, intervals-7 and 17 of reservoir-3 and intervals-5, 8 and 13 of reservoir-4 have expelled into the range between lower limit and its predecessor value whereas, the discharge at intervals-4, 7, 14, 20 and 23 of reservoir-1, intervals-7, 18 and 23 of reservoir-2, intervals-3 and 12 of reservoir-3 and intervals-1, 3, 7, 10, 11, 16, 18 and 21 of reservoir-4 have expelled into the range between upper limit and its successor value.

Table 1. Hourly optimal water discharge of hydro plant with PDZ

	Water Discharge 10^4 m^3			
Hours	Q_{h1}	Q_{h2}	Q_{h3}	Q_{h4}
1	5.8396	6.5294	10.4380	18.7117
2	12.1828	12.0442	13.7134	15.5717
3	5.3315	6.3428	27.7581	18.8268
4	9.5715	10.4846	13.7046	8.2341
5	7.4966	13.1354	16.1091	15.8209
6	11.4280	6.8419	15.3159	12.4554
7	9.9171	8.1954	21.3587	18.9668
8	5.8972	9.8902	13.3745	15.4481
9	13.5628	10.1268	11.7949	19.5540
10	5.0158	6.3039	10.2108	18.7453
11	13.7557	6.5304	16.0622	18.9861
12	10.8071	6.1188	27.1977	14.6180
13	6.7347	11.1495	11.4431	15.5520
14	9.8434	9.3853	12.8345	10.1617
15	6.4970	6.5757	10.6741	19.7109
16	5.2853	6.2995	19.4576	18.7552
17	5.5313	10.4988	21.2655	19.7592
18	5.5582	8.8035	13.9120	18.0299
19	7.0721	6.5244	12.4099	14.6046
20	9.0643	11.2034	19.7086	13.7591
21	7.2077	9.8544	10.2876	18.7936
22	7.3473	10.0917	14.4293	13.8213
23	9.7437	8.1487	11.4467	10.3132
24	6.8498	6.6244	15.0740	9.9661

The cost effective hydrothermal dispatch, total generation and line loss are given in Table 2 and it shows the lower and upper Ramp Rate Limits (RRL) have controlled the thermal power generation not to increase or decrease an amount of UR and DR respectively. Additionally, the total generation and loss have balanced the power balance constraint (3) at each interval for particular load demand.

The water stored in a reservoir from beginning to end of the scheduling period is recorded in the Figure 1. It shows that the solution repair mechanism has handled hydraulic continuity equation effectively. Thus, the initial and final reservoir storage volume constraints are satisfied fully. Further, the steady and stable convergence characteristic is depicted in Figure 2 and revels that the algorithm has converged at a minimum fuel cost $ 41830.1811.

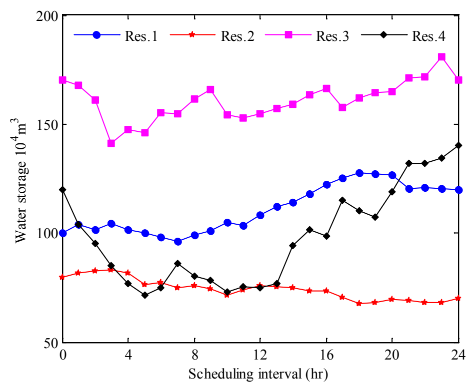

Figure 1. Reservoirs storage volume for cost effective dispatch.

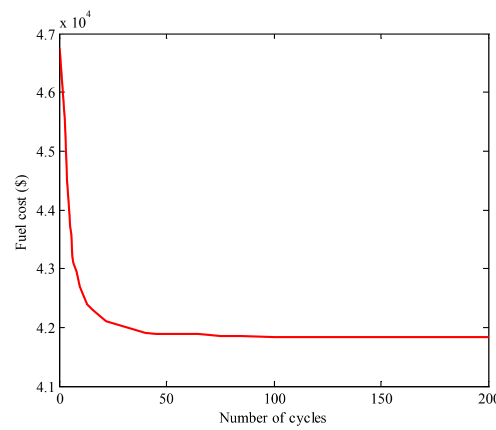

Figure 2. Convergence characteristic of ABC for cost effective dispatch.

Table 2. Hourly optimal HTPS generation schedule, total generations and line loss with PDZ and ramp-rate limit

Hrs	Hydro Generations (MW)				Thermal Generations (MW)			Total Generation (MW)	P_L (MW)
	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}		
1	60.4985	53.5455	56.4614	233.3952	21.6110	124.8711	207.0661	757.4488	7.4488
2	90.9262	79.4772	55.4265	200.7551	93.5781	40.0007	229.5072	789.6711	9.6711
3	59.5076	68.6579	0.0000	191.0145	20.6300	130.0007	239.4197	709.2305	9.2305
4	84.5355	75.7641	53.6730	114.2218	66.3546	97.1297	164.0307	655.7094	5.7094
5	81.3580	66.4623	45.9428	102.3618	20.0000	130.1632	232.2712	678.5593	8.5593
6	80.2064	50.5796	54.5857	161.2746	100.0000	125.2345	239.1586	811.0394	11.0394
7	84.2047	59.9295	60.6449	239.4739	104.0599	174.5695	239.0315	961.9138	11.9138
8	72.8261	78.5290	68.7625	283.7293	104.0017	174.4460	239.4348	1021.7293	11.7293
9	73.6920	86.2721	87.9919	336.2377	104.1348	174.3043	239.1418	1101.7745	11.7745
10	67.7565	64.2056	52.1000	389.5122	104.6948	174.4862	239.1568	1091.9121	11.9121
11	84.3307	71.5060	80.0000	357.8275	104.5787	174.2483	239.2924	1111.7836	11.7836
12	74.4418	88.5962	84.7106	395.5372	104.7026	174.2401	239.4401	1161.6686	11.6686
13	74.7666	83.7955	83.8269	361.8293	104.3694	174.2645	239.0109	1121.8632	11.8632
14	68.4281	89.2708	68.0998	298.1529	104.0741	174.5075	239.1901	1041.7231	11.7231
15	75.8544	71.1838	77.6438	278.5910	104.7697	174.3556	239.5845	1021.9828	11.9828
16	88.4898	78.9966	86.8365	298.9108	104.6771	174.8689	239.0647	1071.8444	11.8444
17	77.8125	86.8665	89.4500	289.4223	104.3577	174.7943	239.1871	1061.8904	11.8904
18	80.3407	98.0866	87.1755	348.3713	104.8661	174.0625	239.0033	1131.9061	11.9061
19	73.2361	84.9373	77.8486	326.5854	104.5846	174.9225	239.6841	1081.7986	11.7986
20	76.1172	57.2592	64.9386	344.7293	104.8438	174.6202	239.0997	1061.6080	11.6080
21	104.1383	61.8848	58.7807	231.7753	104.7741	129.3751	230.2322	920.9605	10.9605
22	74.8915	64.7923	58.8627	231.5434	86.9776	123.7192	229.2701	870.0567	10.0567
23	90.2263	54.8717	59.7931	198.3723	104.7124	122.6935	229.9559	860.6254	10.6254
24	92.4102	58.0053	0.0000	215.0409	83.9806	121.7901	239.2643	810.4913	10.4913
	Fuel Cost ($) 41830.1811					Emission (lb) 18133.6987			

5.2 Solution Quality Improvement

In order to reveal the superiority of the ABC algorithm in solving economic load dispatch of HTPS with practical constraints, the minimum fuel cost and computational time are compared with the values that have been obtained by IDE[13] and ICHDE[14] techniques in Table 3. From the comparison, it is noticed that the proposed algorithm minimizes the fuel cost ($41830. 1811) with less computational time. This is around $ 1960 and $241 lower than IDE[13] and ICHDE[14] respectively and also seems to be considered as savings.

Table 3. Comparison of feasible solution and computational time with other methods

Methods	Economic load dispatch			
	EC ($)	ER (lb)	Com. Time (s)	Eq. Com. Time (s)
IDE[13]	43790.3300	---	391.12	690.21
ICHDE[14]	42071.5500	---	17.54	20.64
ABC	41830.1811	18133.6987	25.35	25.35

The solution quality improvement over the state of the-art, literature can be explored by comparative analysis; therefore the feasible solution for economic load dispatch is statically analyzed and the test results are presented in Table 4. It is noticed that the ABC algorithm has determined the best energy cost $41830. 1811 over thirty trials and lower standard deviation confirms the solution quality.

Table 4. Statistical comparisons of feasible solutions

Methods	EC ($)			
	Best	Average	Worst	Std. Dev.
IDE[13]	43790.33	43800.51	43812.01	15.3301
ICHDE[14]	42071.55	42115.87	42132.78	43.2961
ABC	41830.18	41842.46	41850.92	14.6646

5.3 Effect of Practical Constraints

As shown in Figures 3 and 4, the optimal hourly water discharge rate and storage volume of the reservoir without

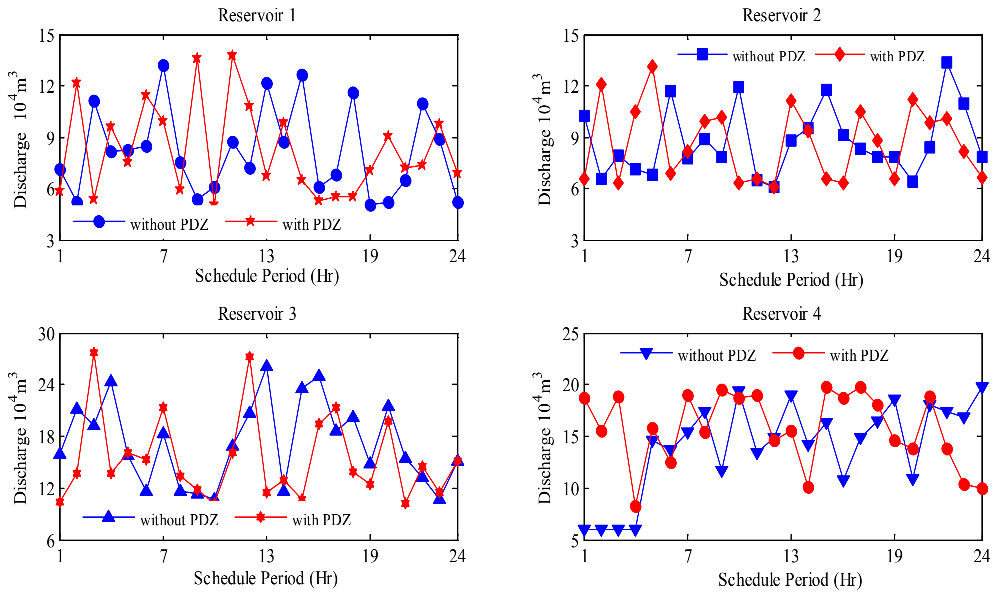

Figure 3. Comparison of optimal hydro discharge for cost effective dispatch.

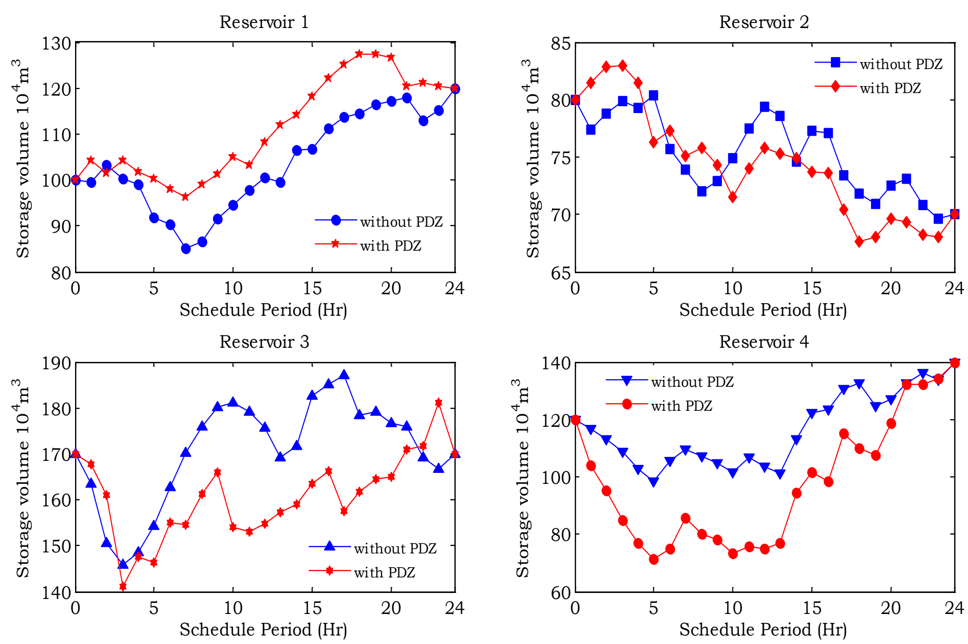

Figure 4. Comparison of reservoir storage volume for cost effective dispatch.

and with PDZ cases have been compared and the effect is summarized in Figure 5. It is clearly identified that the discharge has reduced to 2.2318*10^4 m^3 in case of with PDZ consequently the reservoir storage volume during schedule horizon has reduced to 547.7922*10^4 m^3.

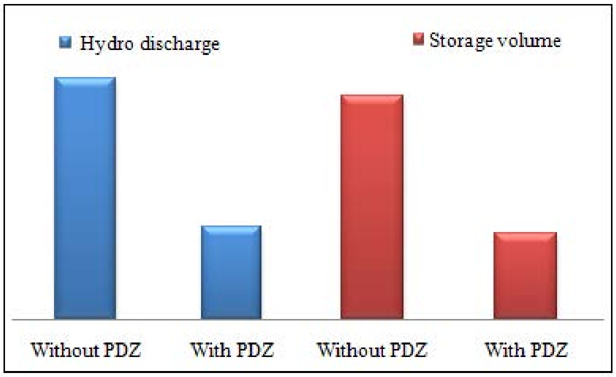

Figure 5. Effect of PDZ on hydro discharge and storage volume for cost effective dispatch.

The inclusion of PDZ of hydro reservoir and ramp rate limit of thermal plant leads to multiple minima's in the search space. Thus, the thermal generation has increased 1.7637%, than without PDZ and RRL[18] for economic load dispatch and the same amount decreased in hydro generation and this is illustrated in Figure 6. The subsequent increase in fuel cost, emission release and computational time are shown in Figure 7.

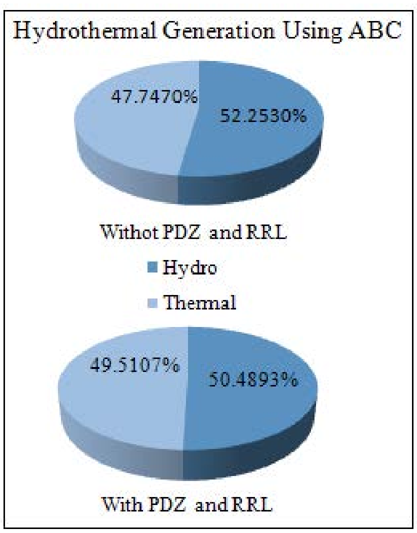

Figure 6. Effect of PDZ and RRL on total generation for cost effective dispatch.

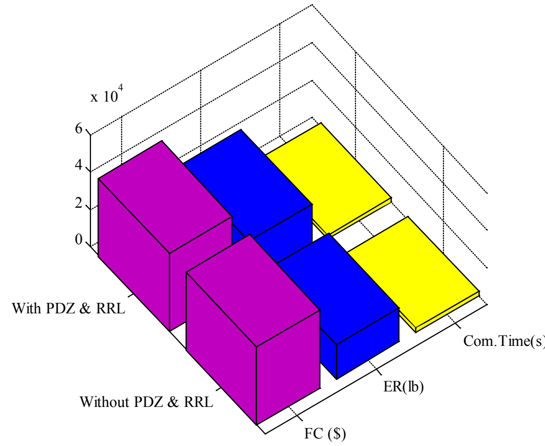

Figure 7. Effect of PDZ and RRL on feasible solutions for cost effective dispatch.

6. Conclusion

This paper has presented a solution procedure in hydrothermal power system using an Artificial Bee Colony algorithm for obtaining cost effective generation schedule. In which, the non-convex non-linear relationship of power generation characteristics and the complicated coupling among hydro reservoirs, water transport time delays, Prohibited Discharge Zones and ramp rate limit are successfully implemented. Furthermore, a heuristic solution repair method is employed to handle power balance and a hydraulic continuity equation. The ABC algorithm is executed for a standard hydrothermal system that consist four hydro and three thermal units and it has converged at feasible solution corresponding to new cost effective generation schedule with less computational time. Additionally, a detailed analysis about the effect of PDZ and ramp rate limit is presented systematically. The comparison reveals that the ABC method outperforms other contestant algorithm in terms of solution quality. Further, the numerical results help provide to serve electricity in affordable price to the society and it would be useful for regulatory bodies to develop energy efficiency projects for securing energy through power system planning.

7. References

1. Kothari DP, Dhillon JS. Power system optimization. 2nd ed.

New Delhi, India: PHI Learning Private Limited; 2011.
2. Blum C, Roli A. Meta-heuristics in combinatorial optimization: Overview and conceptual comparison. ACM Computing Surveys. 2003 Sep; 35(3):268–308. Crossref
3. Wong KP, Wong YW. Short-term hydrothermal scheduling. Part 1: Simulated annealing approach. Proceeding of Generation Transmission Distribution. 1994 Sept; 141(5):497–501. Crossref
4. Orero SO, Irving MR. A Genetic Algorithm modeling framework and solution technique for short term optimal hydrothermal scheduling. IEEE Transactions on Power Systems. 1998 May; 13(2):501–18. Crossref
5. Hota PK, Chakrabarti R, Chattopadhyay PK. Short-term hydrothermal scheduling through evolutionary programming technique. Electric Power System Research. 1999 Nov; 52(2):189–96. Crossref
6. Mandal KK, Basu M, Chakraborty N. Particle Swarm Optimization technique based short-term hydrothermal scheduling. Applied Soft Computing. 2008 Sep; 8(4):1392–9. Crossref
7. Mandal KK, Chakraborty N. Differential Evolution technique based short term economic generation scheduling of hydrothermal systems. Electric Power System Research. 2008 Nov; 78(11):1972–9. Crossref
8. Nguyen TT, Vo DA, Truong AV. Cuckoo search algorithm for short-term hydrothermal scheduling. Applied Energy. 2014 Nov; 132(1):276–87. Crossref
9. Wong SYW. Hybrid simulated annealing/Genetic Algorithm approach to short-term hydrothermal scheduling with multiple thermal plants. Electric Power and Energy System. 2001 Oct; 23(7):566–75.
10. Sivasubramani S, Shanti Swarup K. Hybrid DE–SQP algorithm for non-convex short term hydrothermal scheduling problem. Energy Conversion and Management. 2011 Jan; 52(1):757–61. Crossref
11. Fua X, Li A, Wang L, Ji C. Short-term scheduling of cascade reservoirs using an immune algorithm-based Particle Swarm Optimization. Computers and Mathematics with Applications. 2011 Sep; 62(6):2463–71. Crossref
12. Dubey HM, Pandit M, Panigrahi BK. Cuckoo search algorithm for short term hydrothermal scheduling. Power Electronics and Renewable Energy Systems. 2014 Nov; 326:573–89.
13. Basu M. Improved Differential Evolution for short-term hydrothermal scheduling. Electric Power and Energy System. 2014 Jun; 58:91–100. Crossref
14. Malik TN, Zafar S, Haroon S. An improved chaotic hybrid Differential Evolution for the short-term hydrothermal scheduling problem considering practical constraints. Frontiers Information Technology and Electronic Engineering. 2015 May; 16(5):404–17.
15. Rasoulzadeh-akhijahani A, Mohammadi-ivatloo B. Short-term hydrothermal generation scheduling by a modified dynamic neighborhood learning based Particle Swarm Optimization. Electric Power and Energy System. 2015 May; 67:350–67. Crossref
16. Karaboga D. An idea based on honey bee swarm for numerical optimization. Technical Report-06. 2005; 39(3):1228–37.
17. Karaboga D, Basturk B. A powerful and efficient algorithm for numerical function optimization: Artificial Bee Colony (ABC) algorithm. Journal of Global Optimization. 2007 Nov; 39(3):459–71. Crossref
18. Moorthy V, Sangameswararaju P, Viswanatharao J, Ganesan S, Subramanian S. Cost/environmentally compromised dispatch for cascaded hydrothermal system using Artificial Bee Colony algorithm. IEEJ Trans on Elect and Electron Eng. 2015 Oct; 10:S42–54.