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

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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. 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.
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.

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, Genetic Algorithm (GA) an Evolutionary Programming (EP), Particle Swarm Optimization (PSO), Differential Evolution (DE) approaches and cuckoo search algorithm 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), Differential Evolution–Sequential Quadratic Programming (DE-SQP), immune algorithm–PSO, 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 nonlinear, 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). Meanwhile, Base has examined HTS problem with PDZ and ramp-rate limit of the thermal plant using Improved Differential Evolution (IDE). Moreover, Malik et al. has exercised an improved chaotic hybrid differential evolution, including PDZ and ramp-rate limit of thermal plant (ICHDE) whereas, Rasoulzadeh-akhijahani has implemented dynamic neighborhood learning based PSO for solving HTS with PDZ alone.

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 and the HTS problem 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:

\[
\text{Minimize } F = \sum_{i=1}^{N_s} \sum_{n=1}^{N} t_n^i \left( f_{i,n} \left( P_{n,s}^i \right) \right) \text{ (S)}
\]

Where,

\[
f_{i,n} \left( P_{n,s}^i \right) = a_i + b_i \left( P_{n,s}^i \right) + c_i \left( P_{n,s}^i \right)^2 + d_i \sin \left( e_i \left( P_{n,s}^i - P_{l,i,k} \right) \right)
\]

\[
\text{($/MW - \text{hr}$)}
\]

Where, \(a_i, b_i, c_i, d_i, e_i, f_i\) 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 \(P_{l,i,k}\) is its real power generation.

2.2 System Constraints

2.2.1 Power Balance

\[
\sum_{i=1}^{N_s} P_{s,i,k} + \sum_{j=1}^{N_p} P_{h,j,k} - P_{D,k} - P_{L,k} = 0; \quad k \in T
\]
Where, \( N_h \) is number of hydro units and \( P_{hk} \) 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,

\[
P_{hk} = C_1 h_{k,j}^2 + C_2 h_{k,j}^3 + C_1 h_{k,j} Q_{hk,j} + C_4 h_{k,j} + C_6
\]

(4)

Where, \( C_1, C_2, C_3, C_4, C_5, C_6 \) are power generations coefficients of \( j \)th hydro unit, \( h_{k,j} \) and \( Q_{hk,j} \) are reservoir storage volume and discharge respectively.

2.2.2 Initial and Final Reservoir Storage

\[
V_{h,j}^{k=0} = V_{h,j}^{\text{begin}}, \quad V_{h,j}^{k=T} = V_{h,j}^{\text{end}}; \quad j \in N_h
\]

(5)

2.2.3 Hydraulic Continuity

\[
V_{h,j}^{(k+1)} = V_{h,j}^k + I_{h,j} - Q_{h,j}^k + \sum_{a=1}^{R} \sum_{k=1}^{T} Q_{h,a,j}(k-1)
\]

(6)

Where, \( I_{h,j}, R_u \) and \( \tau \) are natural inflow, number of upstream and water transport time delay to immediate downstream plant respectively.

2.2.4 Generation Limits

\[
P_{hj}^{\text{min}} \leq P_{h,j}^k \leq P_{hj}^{\text{max}}; \quad j = 1, 2, \ldots, N_h
\]

(7)

\[
P_{si}^{\text{min}} \leq P_{s,i}^k \leq P_{si}^{\text{max}}; \quad i = 1, 2, \ldots, N_s
\]

(8)

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

2.2.5 Reservoir Discharge

\[
Q_{h,j}^{\text{min}} \leq Q_{h,j}^k \leq Q_{h,j}^{\text{max}}; \quad j = 1, 2, \ldots, N_h
\]

(9)

Where, \( Q_{h,j}^{\text{min}}, Q_{h,j}^{\text{max}} \) are minimum and maximum hydro discharges of \( j \)th unit respectively.

2.2.6 Reservoir Storage Volume

\[
V_{h,j}^{\text{min}} \leq V_{h,j}^k \leq V_{h,j}^{\text{max}}; \quad j = 1, 2, \ldots, N_h
\]

(10)

Where, \( V_{h,j}^{\text{min}}, V_{h,j}^{\text{max}} \) 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 \( Q_{h,j}, m \) should be imposed:

\[
\begin{align*}
Q_{h,j}^{\text{min}} \leq Q_{h,j}^k \leq Q_{h,j}^{\text{max}} \\
Q_{h,j}^{U,m} \leq Q_{h,j}^k \leq Q_{h,j}^{L,m}; \quad m = 2, 3, \ldots, ND_j
\end{align*}
\]

(11)

Where, \( Q_{h,j}^{L}, Q_{h,j}^{U} \) 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 \( r \)th thermal plant in a certain time interval should not exceed that of the previous time interval by more than a certain prescribed amount \( UR_r \), the upper ramp limit, neither should it be less than that of the previous time interval by more than a certain defined amount \( DR_r \), the down ramp limit of the \( r \)th thermal plant. Mathematically, this constraint is formulated as:

\[
\begin{align*}
P_{s,i}^k - P_{s,i,k-1}^r & \leq UR_r; \text{ if generation increases} \\
P_{s,i}^k - P_{s,i,k-1}^r & \leq DR_r; \text{ if generation decreases}
\end{align*}
\]

(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).

\[ x_{k,l,j} = x_{k,l,j}^{\text{min}} + \text{rand}(0,1)(x_{k,l,j}^{\text{max}} - x_{k,l,j}^{\text{min}}) \]  

Where, \( x_{k,l,j}^{\text{min}}, x_{k,l,j}^{\text{max}} \) are lower and upper boundaries in dimension \( "l" \), \( \text{rand} \) is a random number between [0 1].

**Step 2:** Population is evaluated.

**Step 3:** FOR cycle = 1; REPEAT

**Step 4:** New solutions (food source positions) \( v_{k,l} \) in the neighborhood of \( x_{k,l} \) are produced for the employed bees using (14) is the solution in the \( i \)th neighborhood, \( \phi_{k,l} \) being a random number \((-1 \leq \text{rand} \leq 1) \) and evaluate them.

\[ v_{k,l,j} = x_{k,l,j} + \phi_{k,l}(x_{k,l,j} - x_{m,l,j});k \neq m;m \in \text{SP}; l \in D \]  

**Step 5:** Store the best values between \( x_{k,l,j} \) and \( v_{k,l} \) 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).

\[ P_k = \frac{\text{fit}_k}{\sum_{m=1}^{\text{SP}} \text{fit}_m} \]  

\[ \text{fit}_k = \begin{cases} 1 & \text{if } f(x_k) \geq 0 \\ 1 + \text{abs}(f(x_k)) & \text{if } f(x_k) < 0 \end{cases} \]  

**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 \( x_k \) 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).

\[ Q_{h,j,k} = Q_{h,j}^{\text{min}} + \text{rand}\left(Q_{h,j}^{\text{max}} - Q_{h,j}^{\text{min}}\right) \]  

\[ P_{s,i,k} = P_{s,i}^{\text{min}} + \text{rand}\left(P_{s,i}^{\text{max}} - P_{s,i}^{\text{min}}\right) \]  

Considering Prohibited Discharge Zones (PDZs) of hydro plant, the discharge rate may lie in prohibited regions i.e. \( \left(Q_{h,j}^c < Q_{h,j} < Q_{h,j}^p\right) \). So as to expel the food from PDZs, a constraint for discharge rate represented by (11) should be imposed. Unlike thermal generation the hourly hydrotro 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.

\[ Q_{h,j,d} = v_{h,j}^{\text{begin}} - v_{h,j}^{\text{end}} - \sum_{k=1}^{T} Q_{h,j,k} + \sum_{k=1}^{T} I_{h,j,k} + \sum_{a=1}^{R_i} \sum_{k=1}^{T} Q_{h,a,j} \]  

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

\[ x^o = [Q_{h1} \cdots Q_{h1T} \cdots Q_{h1T} \cdots Q_{h1T} P_{s1} \cdots P_{s1T} \cdots P_{s1T}] \]
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.

\[
AOF = \left( \text{objective} + 1000 \sum_{k=1}^{T} \sum_{m=1}^{N_s+N_h} (P_{m,k} - P_{L_k} - P_{L_k}) \right)
\]  
(21)

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

\[
\text{fit}_i = \begin{cases} 
1 & \text{if } AOF \geq 0 \\
1 + \text{abs}(AOF) & \text{if } AOF < 0 
\end{cases}
\]  
(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.

\[
x_i^{\text{new}} = x_i^{\text{new}} + rand[0,1] (x_i^{\text{new}} - x_i^{\text{old}}); i \in (N_s + N_h)
\]  
(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.

\[
B_{si}P_{s,k}^2 + \left( \sum_{m=1}^{(N_s+N_h)} B_{m,k}P_{m,k} \right)P_{s,k} + \left( \sum_{m=1}^{(N_s+N_h)-1} B_{m,k}P_{m,k} + B_{si} + P_{th} \right) = 0; k \in T
\]  
(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:

\[
Q_{hj,k} = \begin{cases} 
Q_{hj,m}^{L} + rand \leq 0.5 \\
Q_{hj,m}^{U} + rand > 0.5 
\end{cases} m = 2,3,..ND
\]  
(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:

\[
P_{si,k}^{\text{max}} = \min \left\{ P_{si,k}^{\text{max}}, \left( P_{si,k-1} + UR \right) \right\}
\]
(26)

\[
P_{si,k}^{\text{min}} = \max \left\{ P_{si,k}^{\text{min}}, \left( P_{si,k-1} - DR \right) \right\}
\]

\[
P_{si,k}^{\text{min}} \leq P_{si,k} \leq P_{si,k}^{\text{max}}
\]

Step 7: Evaluation of the Stopping Condition

If \(\text{iter} \leq \text{max Cycle}\), go to step 3. Otherwise, the ABC algorithm terminates.

5. Simulation Results and Discussion

The practical constraints of PDZ15 on the hydro reservoir discharge and the ramp-rate limit15 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 period1. 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 successor 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 predecessor value.

| 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](https://example.com/figure1.png)

Figure 1. Reservoirs storage volume for cost effective dispatch.

![Figure 2](https://example.com/figure2.png)

Figure 2. Convergence characteristic of ABC for cost effective dispatch.
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 and ICHDE 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 and ICHDE respectively and also seems to be considered as savings.

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

| Methods | EC ($) | ER (lb) | Com. Time (s) | Eq. Com. Time (s) |
|---------|--------|---------|---------------|------------------|
| IDE | 43790.3300 | --- | 391.12 | 690.21 |
| ICHDE | 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 ($) |
|---------|--------|
| IDE | 43790.33 | 43800.51 | 43812.01 | 15.3301 |
| ICHDE | 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 $2.2318 \times 10^4$ m$^3$ in case of with PDZ consequently the reservoir storage volume during schedule horizon has reduced to $547.7922 \times 10^4$ m$^3$.

![Figure 5. Effect of PDZ on hydro discharge and storage volume for cost effective dispatch.](image)

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.

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