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ARTIFICIAL BEE COLONY ALGORITHM FOR SOLVING BI-OBJECTIVE HYDROTHERMAL SCHEDULING WITH PRACTICAL CONSTRAINTS

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ABSTRACT

This paper describes the computational ability of artificial bee colony (ABC) algorithm in ascertaining optimal generation scheduling to the hydrothermal power system so as to minimize the fuel cost and emission release subjected to various operational and practical constraints. The hydrothermal scheduling problem is devised as extremely non-convex and bi-objective optimization under practical constraints and linear interpolated price penalty model is developed based on simple analytical geometry equations which blends two non-commensurable objectives perfectly. In order to obtain high-quality solutions within lesser executing time, an appropriate constraint handling mechanism is suitably incorporated in the algorithm that intern produces a stable convergence characteristic. The effectiveness of the proposed method is illustrated on cascaded hydrothermal power system (HTPS) with due consideration of water transport delay between connected reservoirs, prohibited discharge zone of hydro reservoir, ramp rate limit of thermal unit and transmission loss of system load. The desired ABC algorithm reports a new feasible solution for economic, emission and combined economic and emission dispatch in HTPS with practical constraints which is better than the earlier reports in term of solution quality.

Keywords: hydrothermal generation schedule, artificial bee colony, economic/emission, prohibited discharge zone, ramp-rate.

1. INTRODUCTION

Several 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 [1].

As stated above it is not a problem specific, has less hold on initial solution point and tendency to solve large-scale and any kind of complex engineering problem, the researchers are motivated to solve hydrothermal scheduling (HTS) problem. It can be mathematically formulated as an optimization problem subjected to various operational and physical constraints in a schedule horizon of the time interval so as to ascertain the optimal operation of the hydrothermal power systems (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 [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, Dubey *et al.*, has applied cuckoo search algorithm for solving HTS problem with the hydraulic prohibited discharge zone (PDZ) [12]. Meanwhile, Basu has examined HTS problem with PDZ and ramp-rate limit of the thermal plant using improved DE [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].

To serve electricity, cheapest possible price with cleanliness, environment a suitable optimum operation strategy is developed such that the fuel cost is minimized along with the minimal use of fossil fuel in addition to minimizing the environmental damage. In that respect, multi-objective DE (MODE) [16], surrogate DE (SDE) [17], self organizing-hierarchical PSO technique with

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time-varying acceleration coefficients (SOHPSO_TVAC) [18], an improved GS algorithm (IGSA) [19] and hybrid chemical reaction optimization (HCRO) [20] were minimized fuel cost and pollutant emission simultaneously.

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. Then, 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 [21] - [22] and the HTS problem [23] 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 environmentally constrained HTS problem with practical constraints. Hence, in this paper a preliminary investigation is attempting to explore the versatile characteristics of ABC algorithm viz. (i) optimal values, (ii) feasible solution and (iii) solution quality.

The paper is organized into six sections, in the next section, mathematical formulation of ABC algorithm as an optimization tool is briefed. Section 3 describes the HTS problem, 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. 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.

2.1 Pseudo code of ABC algorithm

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

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

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
Step 4: New solutions (food source positions) v_{kl} in the neighborhood of x_{kl} are produced for the employed bees using (2) is the solution in the i^{th} neighborhood, ϕ_{kl} being a random number ($-1 \leq$ rand ≤ 1) and evaluate them.

$$\begin{aligned} v_{k,l} &= x_{k,l} + \phi_{k,l}\left(x_{k,l} - x_{m,l}\right); \\ & k \neq m; m \in SP; l \in D \end{aligned} \tag{2}$$

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 (3). In this fit represents the fitness values of solutions and these are calculated using (4)

$$p_k = \frac{fit_k}{\sum_{m=1}^{SP} fit_m} \tag{3}$$

$$fit_k = \begin{cases} \dfrac{1}{1+f\left(x_k\right)} & if\ f\left(x_k\right) \geq 0 \\ 1+abs\left(f\left(x_k\right)\right) & if\ f\left(x_k\right) < 0 \end{cases} \tag{4}$$

Step7: 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 (1).
Step 10: Memorize the best food source obtained so far.
Step 11: Cycle = cycle+1
Step 12: UNTIL cycle = Maximum;
Step 13: STOP

3. MATHEMATICAL FORMULATION OF HTS PROBLEM

3.1 Objective functions

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

$$F(P_{si,k}) = \sum_{k=1}^{T}\sum_{i=1}^{N_s} t_k \Big[a_i + b_i P_{si,k} + c_i P_{si,k}^2 + \left| d_i \sin\left\{ g_i \left(P_{si}^{\min} - P_{si,k} \right) \right\} \right| \Big] (\$) \quad (5)$$

$$E(P_{si,k}) = \sum_{k=1}^{T}\sum_{i=1}^{N_s} t_k \Big[\alpha_i + \beta_i P_{si,k} + \gamma_i P_{si,k}^2 + \eta_i \exp\left(\delta_i P_{si,k} \right) \Big] \, (lb) \quad (6)$$

Where, a_i, b_i, c_i *and* e_i, f_i are coefficients of the cost curve and valve point effect of i^{th} thermal unit respectively whereas, $\alpha_i, \beta_i, \gamma_i, \eta_i, \delta_i$ are emission curve coefficients. 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.

3.2 System constraints

A. Power balance

$$\sum_{i=1}^{N_s} P_{s,ik} + \sum_{j=1}^{N_h} P_{h,jk} - P_{D,k} - P_{L,k} = 0; \; k \in T \quad (7)$$

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,

$$P_{h,j} = C_{1j} V_{h,j}^2 + C_{2j} Q_{h,j}^2 + C_{3j} V_{h,j} Q_{h,j} + C_{4j} V_{h,j} + C_{5j} Q_{h,j} + C_{6j} \quad (8)$$

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

B. Initial and final reservoir storage

$$V_{h,jk}^{\;k=0} = V_{h,j}^{\;begin}; V_{h,jk}^{\;k=T} = V_{h,j}^{\;end} \quad ; \; j \in N_h \quad (9)$$

C. Hydraulic continuity

$$V_{h(j,k+1)} = V_{hj,k} + I_{hj,k} - Q_{hj,k} + \sum_{u=1}^{R_u}\sum_{k=1}^{T} \Big[Q_{h(u,k-\tau)} \Big] \quad (10)$$

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

D. Generation limits

$$P_{hj}^{\min} \le P_{hj,k} \le P_{hj}^{\max}; P_{si}^{\min} \le P_{si,k} \le P_{si}^{\max} \; ; j = 1,2,....N_h; i = 1,2,....N_s \quad (11)$$

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.

E. Reservoir discharge

$$Q_{h,j}^{\min} \le Q_{hj,k} \le Q_{h,j}^{\max} \quad j = 1,2,....N_h \quad (12)$$

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

F. Reservoir storage volume

$$V_{hj}^{\min} \le V_{hj,k} \le V_{hj}^{\max} \quad j = 1,2.....N_h \quad (13)$$

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

G. 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].

$$\begin{cases} Q_{hj}^{\min} \le Q_{hj,k} \le Q_{hj,1}^{L} \\ Q_{hj,m-1}^{U} \le Q_{hj,k} \le Q_{hj,m}^{L} \; ; m = 2,3,..,ND_j \\ Q_{hj,m}^{U} \le Q_{hj,k} \le Q_{hj}^{\max} \quad ; m = ND_j \end{cases} \quad (14)$$

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

H. 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]:

$$\begin{cases} P_{si,k} - P_{si,k-1} \le UR_i \, ; if \; generation \; increases \\ P_{si,k-1} - P_{si,k} \le DR_i \, ; if \; generation \; decreases \end{cases} \quad (15)$$

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3.3 Formation of bi-objective HTS

The bi-objective hydrothermal scheduling problem can be formulated as simultaneous minimization of fuel cost and emission release and can be expressed as:

$$\text{Minimize } \left\{F(P_{si,k}),\, E(P_{si,k})\right\} \tag{16}$$

Generally, it can be handled by using the price penalty factor approach. While computing price penalty factor, the sum of the maximum capacity of thermal units often greater than demand, it may lead approximate value. In order to determine the no-inferior solution a linear interpolated price penalty approach is employed in this paper.

Let, P_{g1} is the maximum capacity of a unit at that moment by adding the maximum capacity causes sum total exceeds the load demand P_D and its corresponding price penalty factor is h_1. The maximum capacity P_{go} is the predecessor and the associated price penalty is h_o. Then the normalized price penalty factor can be determined using (17).

$$h_k = h_o + \left(\frac{h_1 - h_o}{P_{s1} - P_{so}}\right) * \left(P_{D,k} - P_{so}\right) \tag{17}$$

Now, the objective functions have detailed in (5) and (6) can be defined by introducing h_k, then the objective function of the HTS problem is defined as,

$$\text{Minimize } \left\{F(P_{si,k}) + h_k * E(P_{si,k})\right\} \tag{18}$$

4. IMPLEMENTATION OF ABC FOR SOLVING HTS PROBLEM

The computational procedure of an ABC algorithm for hydrothermal generation schedule is demonstrated in Figure-1. The first step begins by representing algorithm parameter in terms of system variable. Hence, hourly water discharge of hydro plant and the thermal generation are randomly engendered within the operational limits based on (11). As, prohibited discharge zone (PDZ) of hydro plant is considered, the discharge rate may lie in prohibited regions, i.e., $\left(Q_{hj}^{L} < Q_{hj,k} < Q_{hj}^{U}\right)$ should be expelled [15] and also a solution repair mechanism is adopted to satisfy the water continuity constraint. Therefore, a dependent interval "d" was chosen randomly and discharge at that interval was calculated by re-arranging (10) and given by (19). Then, the remaining steps have been described crisply in the flowchart.

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

4.1 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 (7) perfectly.

$$\begin{aligned} & B_{dd}P_{sd,k}^2 + \left(2\sum_{m=1}^{(N_s+N_h)-1} B_{d,m}P_{m,k} - 1\right)P_{sd,k} \\ & + \left(\sum_{m=1}^{(N_s+N_h)-1}\sum_{n}^{(N_s+N_h)-1} P_{m,k}B_{mn}P_{n,k} + \sum_{m=1}^{(N_s+N_h)-1} B_{m,0}P_{m,k} \right. \\ & \left. - \sum_{\substack{m=1\\m\neq d}}^{(N_s+N_h)-1} P_{m,k} + B_{00} + P_{Dk}\right) = 0;\, k\in T \end{aligned} \tag{20}$$

4.2 Inequality constraints handling mechanism

The decision variables of hydro discharge and thermal power generation are kept in the valid range by handling appropriately. Generally, the hydro discharge will be handled using (12). Considering PDZ of hydro plants the discharge rate may be handled using (21) [15].

$$Q_{hj,k} = \begin{cases} Q_{hj,m}^{L} & rand \le 0.5 \\ Q_{hj,m}^{U} & rand > 0.5 \end{cases} \quad m = 2,3,..ND_j \tag{21}$$

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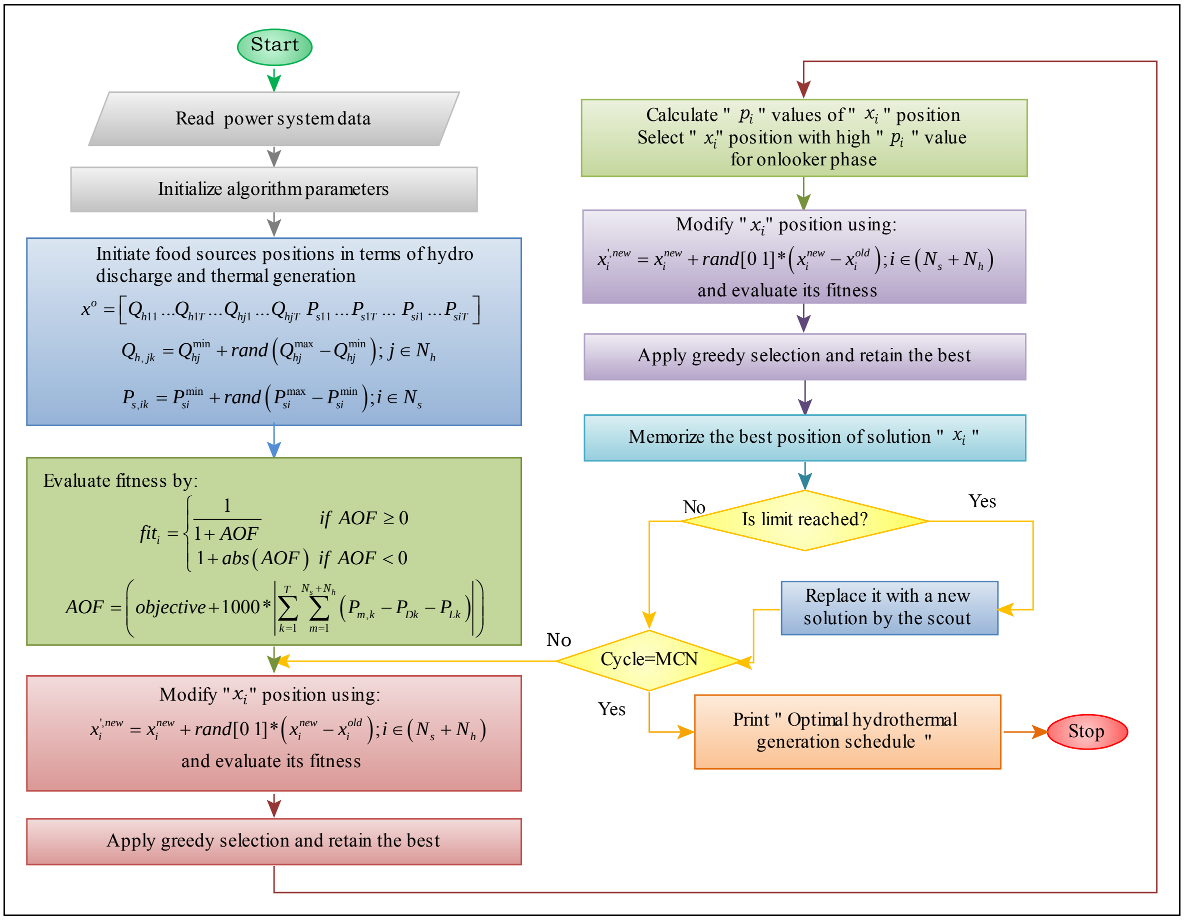

Figure-1. Computational flowchart of ABC for HTS.

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

$$\left.\begin{aligned} P_{si,k}^{r\max} &= \min\left\{P_{si}^{\max}, \left(P_{si,k-1} + UR_i\right)\right\} \\ P_{si,k}^{r\min} &= \max\left\{P_{si}^{\min}, \left(P_{si,k-1} - DR_i\right)\right\} \\ P_{si,k}^{r\min} &\leq P_{si,k} \leq P_{si,k}^{r\max} \end{aligned}\right\} \tag{22}$$

5. SIMULATION RESULTS AND DISCUSSION

In this study 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. The simulation is carried for economic load dispatch (case study-I), minimum emission dispatch (case study-II) separately and combined economic emission dispatch (case study-III).

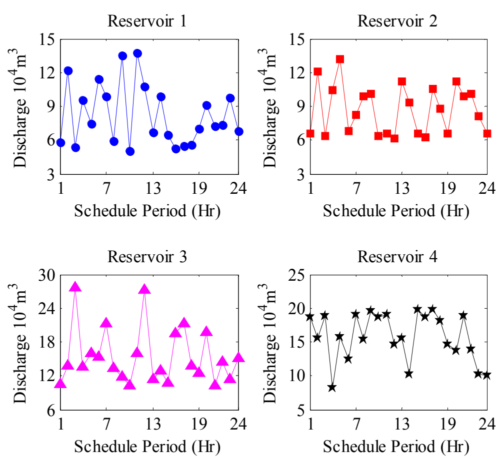

Figure-2. Optimum water discharges for economic load dispatch.

5.1 Economic load dispatch (ELD)

In this case the fuel cost is considered as objective function and the hydro discharge is optimized using an ABC algorithm over a 200 independent iteration with same control variables in conjunction with thermal

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plant real power generation. The optimum hourly hydro reservoir discharge and economic hydrothermal generation corresponding to minimum fuel cost have been presented in Figure 2 and Table 1 respectively. It is observed that the discharges are optimized within the operating limits and also the discharge lie in between PDZ is expelled either below the lower limit or above the upper limit of PDZ. Moreover, 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.

Table-1. Optimum hydrothermal generation for economic load dispatch.

Hrs	**Hydro Generations** (MW)				**Thermal Generations** (MW)		
	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}
1	60.50	53.55	56.46	233.40	21.61	124.87	207.07
2	90.93	79.48	55.43	200.76	93.58	40.00	229.51
3	59.51	68.66	0.00	191.01	20.63	130.00	239.42
4	84.54	75.76	53.67	114.22	66.35	97.13	164.03
5	81.36	66.46	45.94	102.36	20.00	130.16	232.27
6	80.21	50.58	54.59	161.27	100.00	125.23	239.16
7	84.20	59.93	60.64	239.47	104.06	174.57	239.03
8	72.83	78.53	68.76	283.73	104.00	174.45	239.43
9	73.69	86.27	87.99	336.24	104.13	174.30	239.14
10	67.76	64.21	52.10	389.51	104.69	174.49	239.16
11	84.33	71.51	80.00	357.83	104.58	174.25	239.29
12	74.44	88.60	84.71	395.54	104.70	174.24	239.44
13	74.77	83.80	83.83	361.83	104.37	174.26	239.01
14	68.43	89.27	68.10	298.15	104.07	174.51	239.19
15	75.85	71.18	77.64	278.59	104.77	174.36	239.58
16	88.49	79.00	86.84	298.91	104.68	174.87	239.06
17	77.81	86.87	89.45	289.42	104.36	174.79	239.19
18	80.34	98.09	87.18	348.37	104.87	174.06	239.00
19	73.24	84.94	77.85	326.59	104.58	174.92	239.68
20	76.12	57.26	64.94	344.73	104.84	174.62	239.10
21	104.14	61.88	58.78	231.78	104.77	129.38	230.23
22	74.89	64.79	58.86	231.54	86.98	123.72	229.27
23	90.23	54.87	59.79	198.37	104.71	122.69	229.96
24	92.41	58.01	0.00	215.04	83.98	121.79	239.26
Fuel Cost ($) 41830.1811				Emission (lb) 18133.6987			

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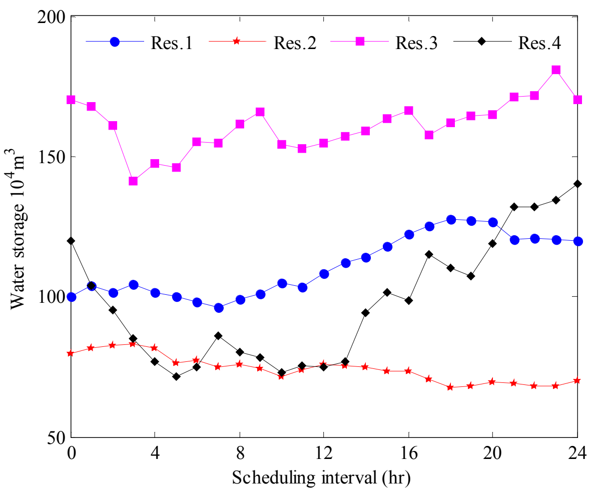

Figure-3. Reservoir storage volume for economic load dispatch.

The water stored in a reservoir from beginning to end of the scheduling period is recorded in the Figure-3. 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-4 and revel that the algorithm has converged at a minimum fuel cost $ 41830.1811.

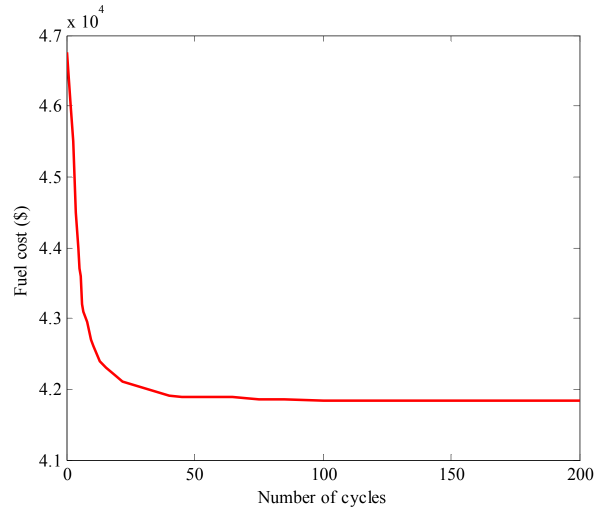

Figure-4. Convergence characteristic of ABC for ELD.

5.2 Minimum emission dispatch (MED)

The ABC algorithm is executed for a 200 independent iteration with the aim of minimizing emission release caused by thermal plant during the real power generation in coordination to the hydro plant. In which the available water resource optimally utilized intent to reduce massive emission releases. Hence, the optimal hydrothermal generation schedule corresponding to minimum emission release is given in Table-2, follows the hourly water discharge is pictured in the Figure-5.

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Table-2. Optimum hydrothermal generation for minimum emission dispatch.

Hrs	Hydro Generations (MW)				Thermal Generations (MW)		
	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}
1	76.05	59.38	53.14	152.07	62.27	122.29	234.08
2	55.77	64.56	54.51	191.68	55.82	174.73	190.32
3	69.30	57.91	0.00	149.03	58.23	174.95	198.42
4	56.95	67.02	52.97	160.81	104.48	113.94	98.42
5	64.21	56.00	55.04	172.38	48.98	160.46	117.17
6	86.35	76.76	56.92	129.61	101.98	174.51	182.50
7	93.71	83.46	77.02	194.10	104.17	174.46	234.55
8	87.45	89.34	87.14	244.62	104.12	174.26	234.67
9	97.54	95.25	95.61	299.80	104.66	174.38	234.07
10	97.66	95.23	98.00	288.01	104.00	174.64	234.13
11	98.24	96.86	96.30	308.63	103.57	173.76	234.14
12	93.46	94.07	98.20	362.78	104.10	174.39	234.55
13	87.28	83.63	88.35	348.27	104.94	174.92	234.03
14	86.37	80.96	83.10	277.69	104.74	174.74	234.08
15	73.84	71.56	72.99	289.95	104.37	174.36	234.67
16	89.12	88.01	85.96	295.45	104.49	174.50	234.45
17	87.97	83.69	83.10	292.78	104.61	174.81	234.91
18	87.33	89.24	85.53	355.88	104.99	174.43	234.18
19	74.39	72.30	77.03	344.31	104.86	174.51	234.16
20	67.73	68.25	67.45	345.37	104.36	174.45	234.09
21	77.33	59.52	58.72	266.69	104.77	174.99	176.90
22	78.94	65.36	62.12	217.27	104.24	174.30	165.96
23	77.17	51.50	58.93	232.64	104.72	174.90	158.04
24	86.13	45.50	47.54	218.52	104.64	160.97	143.86
Emission (lb) 16172.0528					**Fuel Cost ($) 43534.9608**		

As, like ELD the reservoir discharge rate has satisfied its inequality constraint (12) and besides PDZ constraint nicely. Further, it has come to know that the optimized thermal generation within its operating limits and fulfilled upper and lower ramp rate limits, computed hydro power generation from optimal discharge and storage volume inside the power generation limits. Figure 6 illustrates the reservoir water storage volume for all intervals which is computed from optimized water discharge rate and tidily represented trajectories confirms that the algorithm has satisfied equality constraint (9). The fast and stable convergence characteristic of the ABC algorithm for reasonable emission release 16172.0528 (lb) is shown in Figure-7.

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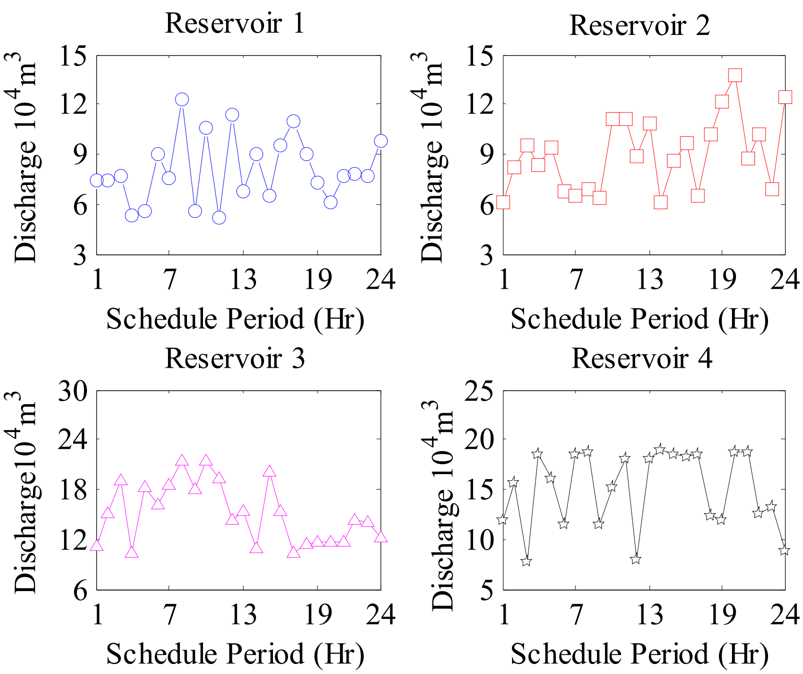

Figure-5. Optimum water discharges for minimum emission dispatch.

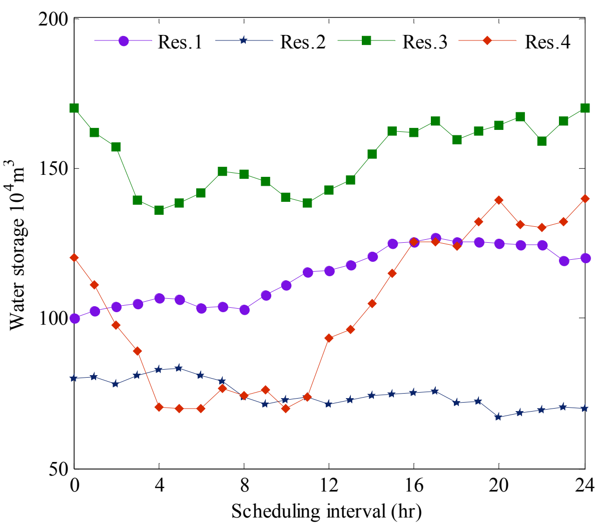

Figure-6. Reservoir storage volume for minimum emission dispatch.

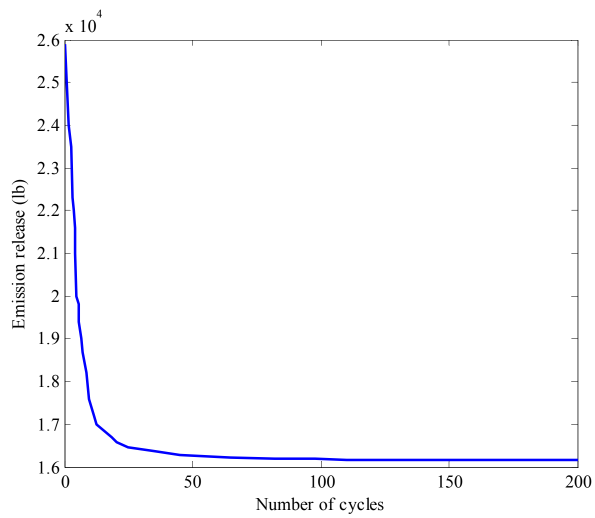

Figure-7. Convergence characteristic of ABC for minimum emission.

5.3 Combined economic-emission dispatch (CEED)

In this dispatch the conflict objectives are optimized simultaneously using ABC algorithm and a trade-off solution is obtained with make use of normalized price penalty factor approach. Table 3 shows the optimal hydrothermal generation schedule where, the hydro generation is computed using optimized water discharge and storage volume whereas, thermal generation is optimized directly. The ramp rate limit is curbed the thermal unit to generate the power steadily.

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Table-3. Optimum hydrothermal generation for combined economic emission dispatch.

Hrs	Hydro Generations (MW)				Thermal Generations (MW)		
	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}
1	55.39	81.50	57.44	198.55	96.32	125.13	141.86
2	72.49	70.47	56.83	202.59	44.08	167.19	172.77
3	65.07	72.22	54.54	200.42	75.09	103.36	134.36
4	68.66	60.14	58.67	169.56	70.68	97.94	128.91
5	61.60	47.67	54.94	163.29	73.31	111.65	163.43
6	88.73	72.11	51.05	161.50	66.48	171.77	196.38
7	97.91	73.47	66.66	210.47	99.05	172.94	241.27
8	84.69	86.58	77.79	259.71	99.16	172.43	241.09
9	94.27	96.36	89.15	307.48	99.99	172.58	241.67
10	84.47	93.66	97.53	302.45	99.42	172.89	241.40
11	80.37	92.23	99.21	337.31	87.82	172.85	241.23
12	101.47	99.24	80.18	368.15	99.17	172.12	241.37
13	92.16	90.22	88.41	337.81	99.45	172.25	241.23
14	81.51	92.10	80.32	274.32	99.61	172.64	241.03
15	77.17	83.41	86.70	261.27	99.40	172.27	241.56
16	102.60	84.29	81.51	290.74	99.17	172.53	241.11
17	82.39	82.60	84.04	299.36	99.64	172.03	241.70
18	107.61	73.46	82.58	355.07	99.28	172.13	241.60
19	105.91	87.21	82.60	292.81	99.65	172.50	241.32
20	102.02	81.76	88.10	276.76	99.34	172.72	241.02
21	93.15	64.46	63.88	215.87	82.43	160.07	241.04
22	66.89	45.00	58.26	287.27	72.21	110.66	229.54
23	77.55	44.81	69.41	206.81	96.04	124.91	241.41
24	73.31	44.05	57.91	256.86	94.84	126.34	153.58
Fuel Cost ($) 43147.2650				Emission (lb) 16511.3000			

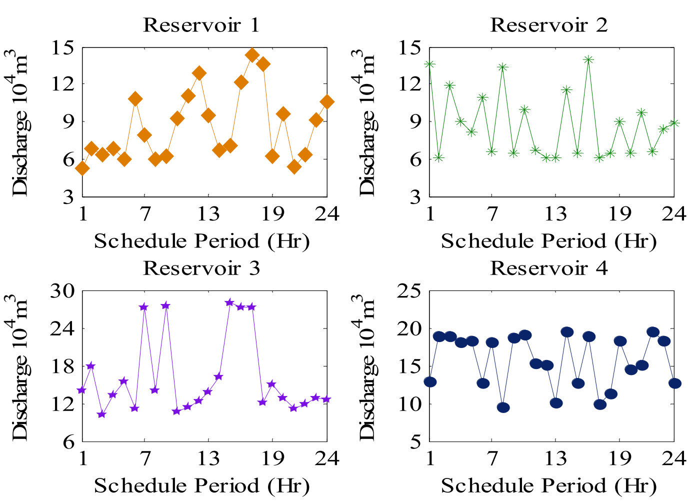

Figure-8. Optimum water discharges for combined economic emission dispatch.

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In the course of hydrothermal optimization problem water discharge is the control variable and it is used to optimize through repetitive iteration, hence the hourly optimal water discharge that has obtained by ABC considering PDZ is presented in Figure-8. The water storage volume has computed using optimal discharge and natural inflow is exemplified in Figure-9. It is understood that the inequality and equality constraints are satisfied completely. Figure-10 shows the optimal fronts that have obtained by the ABC algorithm for thirty independent trials; shows its ability to attain the global minimum in a reliable manner for bi-objective optimization problems.

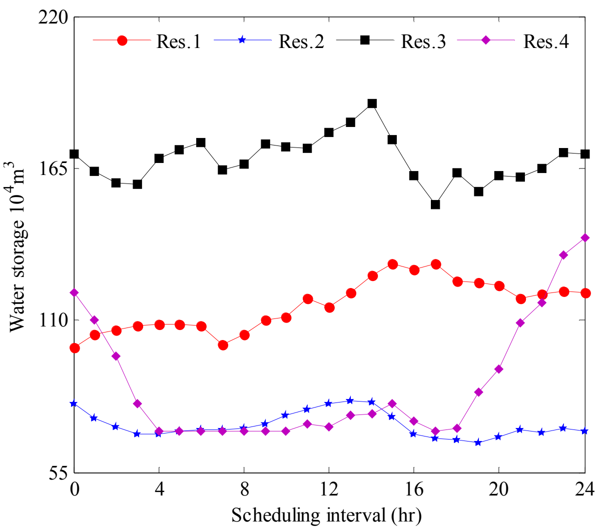

Figure-9. Reservoir storage volume for combined economic emission dispatch.

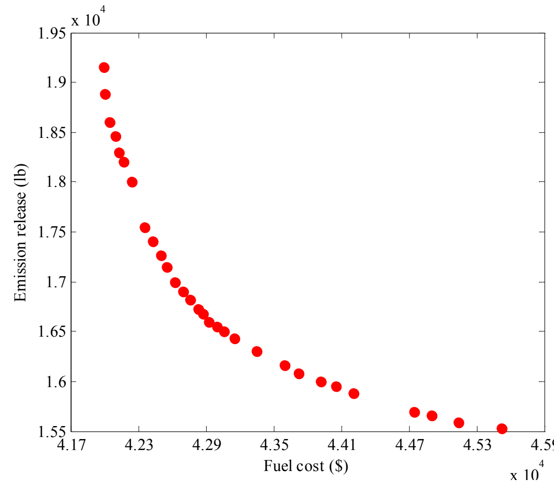

Figure-10. Optimal fronts obtained by ABC for combined economic emission dispatch.

5.4 Feasible solutions and quality improvement

The feasible solutions have obtained by the ABC algorithm for economic load dispatch, minimum emission and combined economic-emission dispatch is listed in Table-4, in which computational time also given.

Table-4. Feasible solutions obtained by ABC in all cases.

	ELD	MED	CEED
FC ($)	**41830.1811**	**43534.9608**	**43147.2650**
ER (lb)	18133.6987	16172.0528	16511.3000
Com. Time (s)	25.35	26.43	29.37

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 ICHDE [14] and IDE [13] techniques in Table-5. From the comparison, it is noticed that the proposed algorithm minimizes the fuel cost into $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-5. Comparison of feasible solution and computational time with other methods for case I.

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

The ABC algorithm is used for determining the optimal output setting of HTPS with practical constraints, the optimal values and feasible solution for different case studies have been presented previously. The solution

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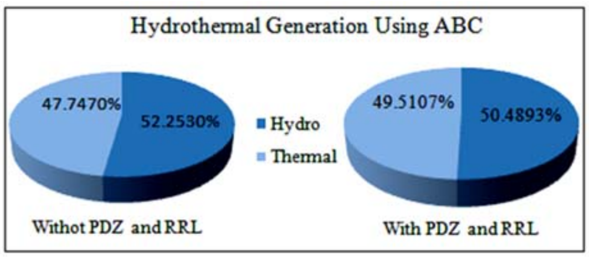
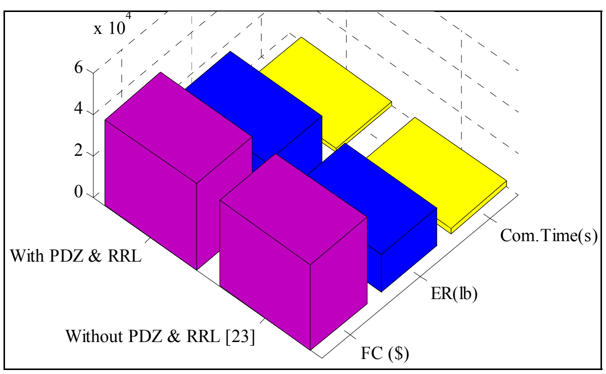
quality improvement over the state of the-art, literature can be explored by comparative analysis; therefore the feasible solution for economic load dispatch is statically analyzed and the test results are presented in Table 6. It is noticed that the ABC algorithm has determined the best energy cost \$41830. 1811 over thirty trials and lower standard deviation confirms the solution quality.

Table-6. Statistical comparisons of feasible solutions for case-I.

Methods	FC (\$)			
	Best	Average	Worst	Std. Dev.
ICHDE [41]	42071.55	42115.87	42132.78	43.2961
IDE [31]	43790.33	43800.51	43812.01	15.3301
ABC	41830.18	41842.46	41850.92	14.6646



(a) Generation

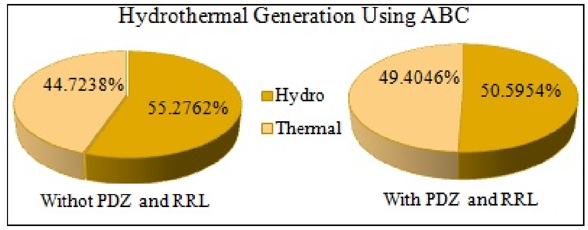


(b) Feasible solutions

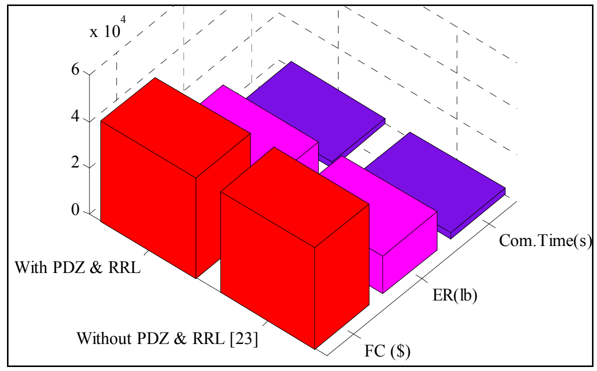
Figure-11. Effects of PDZ and RRL for ELD.

5.5 Effect of practical constraints

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%, 4.6808% and 4.4369% than without PDZ [23] and RRL for ELD, MED and CEED cases respectively and the same amount decreased in hydro generation. These are illustrated in Figures 11 (a), 12 (a) and 13 (a). The consequent increase in fuel cost, emission release and computational time are shown in Figure 11 (b), 12 (b) and 13 (b) for ELD, MED and CEED respectively.

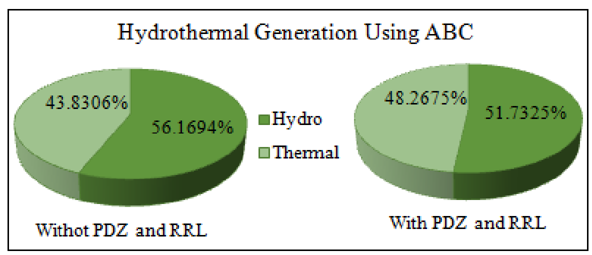


(a) Generation

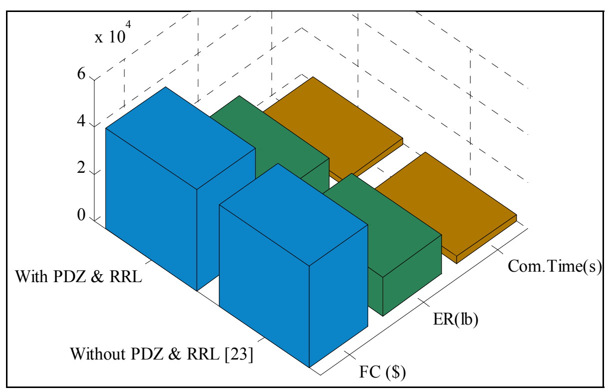


(b) Feasible solutions

Figure-12. Effect of PDZ and RRL for MED.



(a) Generation



(b) Feasible solutions

Figure-13. Effects of PDZ and RRL for CEED.

6. CONCLUSIONS

Hydrothermal scheduling is an imperative forecasting in power system planning and operation, considering pollutant emission is contemporary subject. Therefore, it is modeled as bi-objective optimization subjected to practical constraints; an emerged ABC algorithm is employed that have devised a new generation schedule corresponding to economic load dispatch, minimum emission and compromised dispatch respectively. Further, the numerical results help provide to serve electricity in affordable price with the cleanliness-environment to the society and it would be useful for regulatory bodies, policy makers, renewable energy development agency to develop energy efficiency projects for securing energy through renewable energy resources and power system planners.

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