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Combined Energy Economic and Environmentally Conscious Operation of Hydrothermal Power System Using Artificial Bee Colony Algorithm

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Abstract—*In this paper a solution technique based on artificial bee colony algorithm (ABC) has been implemented to solve hydrothermal scheduling (HTS) problem for energy economic and pollutant emission mitigation by allocating the optimal real power outputs for thermal and hydro electric generators. The HTS is formulated as a bi-objective framework so as to optimize both objectives such as energy cost and emission release simultaneously subjected to verity of complex equality and inequality constraints and normalized price penalty factor is exercised to obtained trade-off between these objectives. Meanwhile, equality constraints are handled efficiently. The performance of the proposed approach is illustrated on multi-chain interconnected hydrothermal power system with due consideration of water transport delay between connected reservoirs and transmission loss of system load. The results obtained from the proposed technique are compared with the other technique. The results demonstrate that the ABC algorithm is feasible and efficient for solving HTS problem, further it is confirmed using standard statistical test using SPSS software.*

Keywords*: Hydrothermal scheduling, Energy economic and environmental issues, Artificial bee colony algorithm, Bi-objectives, Price penalty factor, Descriptive statistics*

1. INTRODUCTION

India is the one of the fourth largest economy and has a fast growing energy market in the world, where the main sources of generating electricity are hydro and coal based thermal power plants. According to twenty second issues of energy statistics 2015, the electricity generation in the country from utilities and non-utilities altogether during 2013-14 were 72.39% from thermal, 11.43% from hydro, 2.90% from nuclear and 13.28% from non-utilities. It shows that the thermal power plant will inevitably dominance impact on environmental effects due to the emission of nitrogen oxides (NOx), sulfur oxides (SOx), greenhouse gases and airborne inorganic particles such as fly ash and soot. These emissions are considered to be partially responsible for global warming, acid rain, smog, and ozone depletion. Therefore, the ministry of environment and forests, India has enacted certain directives under sections 3 and 5 of the environment (protection) act of 1986 via the Gazette notification no. GSR 763 (E) dated 14 September 1999 to meet the requirements of the increasing demand for power with minimal environmental impacts for sustainable development [1-2]. It has been recognized that the energy utilization efficiency improvement and environmental impact assessment are an essential step to achieve sustainable development of a country.

With its rapid economic upgrowth, the rising energy consumption as well as environmental pollution has been impelling the researchers to derive a strategic balance among economic development, energy consumption and environmental sustainability. Recently, the principle of natural selection dependent, evolutionary computation based optimization techniques such as differential evaluation (DE) [3], multi-objective differential evaluation (MO-DE) [4], particle swarm optimization (PSO) [5], are widely employed to attain optimal hydrothermal scheduling intent for obtaining minimum emission release and energy efficient operation subjected to physical and operational constraints of both hydro and thermal power plants. Followed, interactive fuzzy satisfying method based on evolutionary programming technique [6], hybrid multi-objective cultural algorithm [7], self-organizing hierarchical particle swarm optimization technique with time-varying acceleration coefficients (SOHPSO_TVAC) [8], simulated annealing based multi-objective cultural differential evolution (SA-MOCDE) [9], improved gravitational search algorithm (IGSA) [10], dynamically controlled particle swarm optimization (DC-PSO) [11] and hybrid chemical reaction optimization (HCRO) [12].

It is well noticed that the bi-objective is handled using price penalty factor approach and the procedure observed may be yield approximate price penalty factor, whereas the pareto-optimal front is obtained from the archives of the randomly generated parent vector and the trial vector generated by evolutionary search over the individuals of the population in case multiobjective framework.

In this paper combined energy economic and pollutant emission (CEEPE) is formulated as bi-objective optimization problem subjected to several equality, inequality constrains and the effect of valve point loading are also included in the problem formulation. Then a modified price penalty factor is introduced to convert bi-objective into single objective, where linear interpolation method is used to normalize the approximate value of price penalty factor with respect to the load demand of that interval. Further, modified constraint handling mechanism is employed to ensure global optimal solution. Aiming at above interpretation, artificial bee colony (ABC) algorithm has in mind to employ in this work [13, 14]. Thus, it has been exercised and optimal scheduling was obtained with minimum pollutant emission and energy efficiency utilization improvement. Moreover, a standard statistical test [15] is exercised to discriminate the effectiveness the proposed ABC algorithm while minimizing pollutant emission and energy cost on hydrothermal power system.

2. PROBLEM FORMULATION

The mathematical formulation of hydrothermal scheduling is described as follows:

2.1 Energy Economic Objective (EEO)

The energy economic objective in hydrothermal scheduling concern is to minimize the fuel cost of N_s thermal power plants over a scheduling period T, while making use of the availability of hydro-resources as much as possible. The effect of valve-point loading is considered by adding a sinusoidal function to the quadratic cost function. Therefore, the EEO is defined as:

$$\text{Minimize } F=\sum_{t=1}^{T}\sum_{i=1}^{N_s}\left[a_{si}+b_{si}P_{si,t}+c_{si}P_{si,t}^2+\left|e_{si}\sin\left\{f_{si}\left(P_{si}^{\min}-P_{si,t}\right)\right\}\right|\right] \quad (1)$$

Where, F is total generation cost in \$, a_{si}, b_{si}, c_{si} are coefficients of the fuel cost curve of i^{th} thermal unit and e_{si}, f_{si} Valve point effect coefficient of i^{th} thermal unit.

2.2 Pollutant Emission Objective (PEO)

The pollutant emission objective can be described as the attempt to minimize the total emission amount of all the thermal units in the hydrothermal system during the entire operation period, which can be formulated as:

Minimize

$$E=\sum_{t=1}^{T}\sum_{i=1}^{N_s}\left[\alpha_{si}+\beta_{si}P_{si,t}+\gamma_{si}P_{si,t}^2+\eta_{si}\exp\left(\delta_{si}P_{si,t}\right)\right] \quad (2)$$

Where, E is total amount of emission release in lb and $\alpha_{si}, \beta_{si}, \gamma_{si}, \eta_{si}, \delta_{si}$ are emission curve coefficients of ith thermal plant.

2.3 Constraints

2.3.1 Power balance constraints

Let, N_h is number of hydro units, $P_{si,t}$ Generation of i^{th} thermal unit in t^{th} sub interval, $P_{hj,t}$ Generation of j^{th} hydro unit in t^{th} sub interval, $P_{D,t}$ Total power demand in the t^{th} interval, $P_{L,t}$ Total network loss in the t^{th} interval

It is mathematically expressed as:

$$\sum_{i=1}^{N_s}P_{si,t}+\sum_{j=1}^{N_h}P_{hj,t}-P_{D,t}-P_{L,t}=0 \quad (3)$$

The transmission loss may be calculated by using B-loss coefficient matrix directly [7]. As the generated hydro power of any hydro plant in each time period is a function of water discharge rate ($Q_{hj,t}$) of j^{th} reservoir at time t and reservoir storage volume ($V_{hj,t}$) of j^{th} reservoir at time t, which can be described by as follow:

$$\begin{aligned}P_{hj,t}&=C_{1j}V_{hj,t}^2+C_{2j}Q_{hj,t}^2+C_{3j}V_{hj,t}Q_{hj,t}\\&\quad+C_{4j}V_{hj,t}+C_{5j}Q_{hj,t}+C_{6j}\end{aligned} \quad (4)$$

Where, $C_{1j}, C_{2j}, C_{3j}, C_{4j}, C_{5j}, C_{6j}$ are power generation coefficients of j^{th} hydro unit.

2.3.2 Initial and final reservoir storage constraints

The equality constraint is mathematically expressed as follows:

$$V_h(j,t)\,|^{t=0}=V_h(j)^{begin};V_h(j,t)\,|^{t=T}=V_h(j)^{end} \quad (5)$$

2.3.3 Hydraulic continuity constraint

The continuity equation neglecting spillage is given by

$$\begin{aligned}V_h(j,t+1)&=V_h(j,t)+I_h(j,t)-Q_h(j,t)\\&\quad+\sum_{m=1}^{R_u}\sum_{t=1}^{T}Q_h(m,t-\tau)\end{aligned} \quad (6)$$

Where, I_h is natural inflow of j^{th} hydro reservoir at time t, R_u is number of upstream plants and τ Water transport time delay to immediate downstream plant in hours

2.3.4 Power generation constraints

The inequality constraints are mathematically expressed as follows:

$$P_{si}^{\min}\le P_{si,t}\le P_{si}^{\max} \qquad i=1,2,....N_s \quad (7)$$

Where, $P_{si}^{\min}$, $P_{si}^{\max}$ are minimum and maximum generation limit of i^{th} thermal unit.

$$P_{hj}^{\min}\le P_{hj,t}\le P_{hj}^{\max} \qquad j=1,2,....N_h \quad (8)$$

Where, $P_{hj}^{min}, P_{hj}^{max}$ are minimum and maximum generation limit of jth hydro unit.

2.3.5 The water discharge constraint

The plant discharge limit must lie in between its maximum (Q_{hj}^{max}) and minimum (Q_{hj}^{min}) operating limits, as given by

$$Q_{hj}^{min} \le Q_{hj,t} \le Q_{hj}^{max} \quad j = 1, 2, ...N_h \tag{9}$$

2.3.6 Reservoir water storage constraints

The water storage capacity of jth reservoir at each hour must be within its minimum (V_{hj}^{min}) and maximum (V_{hj}^{max}) limits as given below:

$$V_{hj}^{min} \le V_{hj,t} \le V_{hj}^{max} \quad j = 1, 2.....N_h \tag{10}$$

3. AN OVERVIEW OF ARTIFICIAL BEE COLONY ALGORITHM

The artificial bee colony algorithm (ABC) was first proposed by Karaboga for optimizing numerical problems [13, 14]. Basically, ABC algorithm consists of four phases: initialization, employed bees, onlooker bees and scout bees steps.

3.1 Initialization Phase

The initialization process is depicted as follows:

i. Initial population size of SP (twice the number of food sources)
ii. D-dimensional solution vector x_k.
iii. Maximum number of cycle C_{max}
iv. Limit for abandonment of food sources

In this step, SP numbers of food source are placed randomly on D-dimensional problem space by:

$$x_{k,l} = x_{k,l}^{min} + ran[0,1]\left(x_{k,l}^{max} - x_{k,l}^{min}\right) \tag{11}$$

Where, $x_{k,l}$ is kth individual in lth dimension and $x_{k,l}^{min}$, $x_{k,l}^{max}$ are lower and upper ranges of kth food source in dimension l. The search mechanisms of the ABC metaheuristic are explained in detail in the following:

3.2 Employed Bees Phase

In this phase a new food source have been chosen by means of visual information in the neighbourhood of the one in her memory and evaluates its nectar amount. In order to produce a new candidate food position, $v_{k,l}$ from the old one ($x_{k,l}$) in memory, the employed artificial bees update the new food sources by following expression.

$$v_{k,l} = x_{k,l} + \phi_{k,l}\left(x_{k,l} - x_{m,l}\right); \ k \ne m; m \in SP; l \in D \tag{12}$$

Where, $\phi_{k,l}$ is uniform random number between [-1, 1]

3.3 Onlooker Bees Phase

An onlooker prefers a food source area depending on the nectar information distributed by the employed bees on the dance area. The determination of the new food source is carried out by the bees based on the comparison process of food source positions visually and the selection probability of food source i, p_i is calculated by the following expression:

$$p_k = \frac{fit_k}{\sum_{m=1}^{SP} fit_m} \tag{13}$$

3.4 Scout Bees Phase

If onlookers and employed can't improve the location of a food source through a predetermined number of cycles, then that food source is assumed to be abandoned by using the control parameter, "limit". In this case, scout bees try to find a new food source in replacement of the abandoned food source. A new food source location is determined by the Eq. (11).

4. IMPLEMENTATION OF ABC ALGORITHM FOR CEEPE PROBLEM

This section focuses on triumph implementation of ABC algorithm for optimizing short-term hydrothermal scheduling problem in details.

4.1 Initialization of decision variables and initial population

The initialization procedure is summarized as follows:

Step 1: The decision variables of jth hydro plant discharge and the generation of ith thermal unit are randomly generated within the feasible ranges to the constraint (9) and constraint (7) respectively, over the entire scheduling horizon.

Step 2: Then, the initial population x^o is created with length $T*(N_h+N_s)$ and given by

$$x^o = \left[Q_{h,t_1}^1 ...Q_{h,T}^1 ...Q_{h,t_1}^{Nh} ...Q_{h,T}^{Nh} \, P_{s,t_1}^1 ...P_{s,T}^1 ...P_{s,t_1}^{Ns} ...P_{s,T}^{Ns}\right] \tag{14}$$

4.2 Water balance constraint handling

Step 1: Choose a time interval "d" at random as the dependent interval.

Step 2: In order to satisfy the constraint (6) the water discharge rate of the jth hydro plant in the dependent interval "d" is computed using the hydraulic continuity equation as:

$$\begin{aligned} Q_{hj}(d) = V_{hj}^{begin} - V_{hj}^{end} - \sum_{\substack{t=1 \\ t \ne d}}^{T} Q_{hj}(t) + \sum_{t=1}^{T} I_{hj}(t) \\ + \sum_{m=1}^{R_u}\sum_{t=1}^{T} Q_h(m, t-\tau) \end{aligned} \tag{15}$$

Step 3: This process is repeated until the dependent hydro discharge $Q_{hj}(d)$ does not violate its bound constraints (9).

Using the computed hydro discharges, the volumes at different intervals are determined and hydro plant generations are calculated according to hydro plant generation characteristics Eq. (5).

4.3 Load balance constraint handling

The load balance constraint is handled by adjusting the power generation of thermal units. The procedures are [16]:

Step 1: Choose a dependent thermal unit “N_{sd}”. Its dependent generation (i.e., Ps (d, t) is computed by solving Eq. (16) using a standard algebraic method.

$$\begin{aligned} & B_{dd}P_s^2(d,t)+\left(2\sum_{l=1}^{(N_s+N_h)-1} B_{dl}P(l,t)-1\right)P_s(d,t) \\ & +\left(\sum_{l=1}^{(N_s+N_h)-1}\sum_{k}^{(N_s+N_h)-1} P(l,t)B_{lk}P(k,t)\right. \\ & \left.+\sum_{l=1}^{(N_s+N_h)-1} B_{ol}P(l,t)-\sum_{\substack{l=1\\ l\neq d}}^{(N_s+N_h)-1} P(l,t)+B_{oo}+P_D(t)\right)=0;t\in T \end{aligned} \tag{16}$$

Step 2: The positive root is chosen as output of the N_{sd}^{th} thermal generation to satisfy the equality constraint Eq. (3).

4.4 Inequality constraints handling

If any element of the new generated solution is outside the feasible boundaries, then the following procedure will be implemented to modify the value of infeasible elements to satisfy the constraints (7-9):

$$Q_{hj,t}=\begin{cases} Q_{hj}^{min} \text{ if } Q_{hj,t}<Q_{h,j}^{min} \\ Q_{hj}^{max} \text{ if } Q_{hj,t}>Q_{h,j}^{max} \end{cases};j\in N_h;t\in T \tag{17}$$

$$P_{k,t}=\begin{cases} P_k^{min} \text{ if } P_{k,t}<P_k^{min} \\ P_k^{max} \text{ if } P_{k,t}>P_k^{max} \end{cases};k\in(N_h+N_s);t\in T \tag{18}$$

4.5 Handling of Multiple Objectives

The bi-objective optimization problem can be transformed into a single objective optimization problem by employing price penalty factors. As per the defined [17]:

$$h_{max}=\frac{f_{max}}{e_{max}} \quad \$/lb \tag{19}$$

Then the normalized price penalty factor h_t for a particular load demand P_D (MW) is computed using linear interpolation method. Now, the objectives detailed in Eqs. (1) and (2) can be combined by introducing h_t and energy economic and pollutant emission (CEEPE) objective function of HTS problem can be defined as,

$$\text{Minimize} \sum_{t=1}^{T}\sum_{i=1}^{N_s} F_{i,t}\left(P_{si,t}\right)+h_t*E_{i,t}\left(P_{si,t}\right) \tag{20}$$

5. SIMULATION AND RESULTS

The test system considered to conduct this experiment composed by a cascaded four hydro plants where connected in series, parallel and three thermal plants [6]. The total scheduling period is 24 h with an hour interval for each scheduling period and the power loss coefficients are taken from the reference [7]. The control parameters of the ABC algorithm have been adopted as that of Karaboga’s technical report [18] for the present test systems. The developed algorithm has been implemented using MATLAB software package and the programs are executed on an Intel (R) Core (TM) i5-4210C CPU, 1.70GHz, 4-GB RAM computer. The obtained result of test system is compared with the previous methods to validate the solution quality.

5.1 Combined Energy Economic and Pollutant Emission Scheduling (CEEPES)

Here the conflicting objectives are combined using the Eq. (20) and have optimized both energy cost (EC) at $ 42809.8738 and pollutant emission release (PER) at 16402.3726 (lb simultaneously. In this event, the optimal hourly water discharge rate corresponding to minimum energy cost and acceptable pollutant emission release obtained by ABC is shown in Fig. 1. Consequently, hourly optimal hydro plant generation scheduling and thermal generation scheduling have been shown in Figures 2 and 3 respectively.

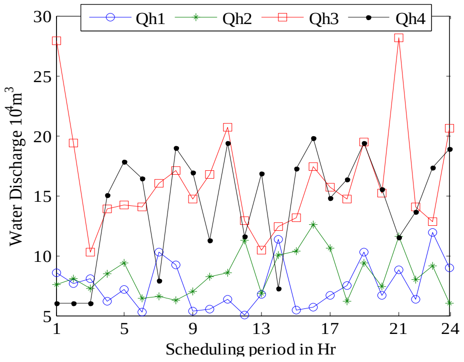

Fig. 1: Hourly optimal water discharge obtained by ABC for CEEPES

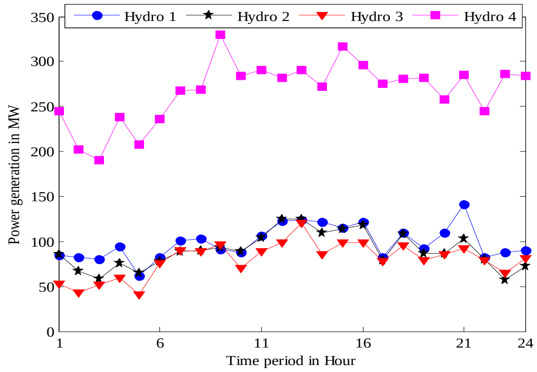

Fig. 2: Hourly optimal hydro plant generation obtained by ABC for CEEPES

5.2 Competency with other method

The best solution was obtained for CEEPES case have been compared in the Table 1, As seen from the result, all the algorithms try to minimize energy cost in the desired values and pollutant emission release in to acceptable value. However, the proposed ABC outperforms other contestant algorithm reported in the literature in view point of pollutant emission reduction and it is able to schedule the hydrothermal system with compromised minimum energy cost and agreeable emission release in CEEPES case. Likewise, the proficiency of proposed ABC method is compared pictorially in Fig. 4, in the Fig. thirty compromised non-inferior solutions obtained by ABC, SA_MOCDE and IGAS were distributed in the operational space. It is clearly seen in the Fig. 4 that non-inferior solutions obtained by ABC has good diversity distribution and dominate those obtained by other three approaches. Furthermore, it reveals that ABC is better to optimize both two objectives and efficient in solving SHTS problem.

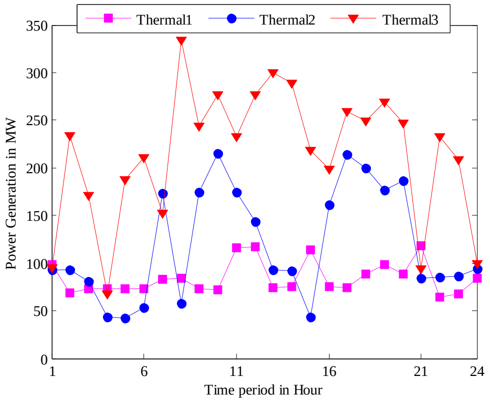

Fig. 3: Hourly optimal thermal plant generation obtained by ABC for CEEPES

Moreover, it is noticed that there is no significant savings in energy cost as compared with DCPSO [16] and HCRO [17] but there is praiseworthy pollutant emission reduction 124.58 (lb) and 1220.64 (lb) respectively. If these two methods have tried to reduce the pollutant emission further the corresponding energy cost will be certainly greater than what the ABC algorithm has obtained.

5.3 Descriptive statistics

A descriptive statistical test was carried out using SPSS software with optimized value of compromised energy cost and pollutant emission over schedule horizon and the experimental results were presented in Tables 2.

Table 1: Comparison of optimal values concerning ABC with other methods

Methods	EC ($)	PER (lb)
DE[3]	44913.51	19614.88
MODE[4]	49677.15	22615.31
PSO [5]	43334.38	18117.09
SOHPSO_TVAC [12]	43045.33	17002.94
SA-MOCDE [14]	43165.12	17464.35
IGSA[15]	43299.75	17868.69
DCPSO[16]	42118.58	16526.95
HCRO[17]	42801.64	17623.01
ABC	42809.87	16402.37

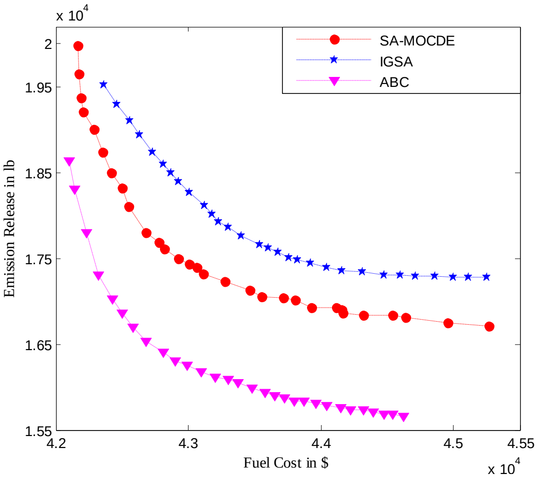

Fig. 4: Distribution of the non-inferior solutions of ABC and solutions of other methods

Table 2: Descriptive statistics for compromised values over schedule horizon

Methods	**Energy Cost in $**			**Rank**		**Pollutant Emission (lb)**			**Rank**
	Mean	**Std. Dev**	**Std Error**			**Mean**	**Std. Dev**	**Std Error**	
DE[3]	1871.40	409.69	83.63	8		817.29	478.15	97.60	8
MODE[4]	2069.88	393.23	80.27	6		942.30	508.68	103.83	9
PSO [5]	1805.60	432.66	88.32	9		754.88	449.26	91.70	7
SOHPSO_TVAC [12]	1793.56	393.53	80.33	7		708.46	386.98	78.99	6
SA-MOCDE [14]	1798.55	287.01	58.59	2		727.68	302.36	61.72	3
IGSA[15]	1804.16	288.86	58.96	3		744.53	295.33	60.28	2
DCPSO[16]	1754.94	345.41	70.51	4		688.62	327.63	66.88	4
HCRO[17]	1783.40	348.03	71.04	5		734.29	340.22	69.45	5
ABC	1783.74	280.10	57.18	1		683.43	288.84	58.96	1

Furthermore, the ranking of each optimization was tabulated according to standard deviation to help provide a clear picture of the consensus reached by the optimization technique. As ABC algorithm have the lowest standard deviation, it is ranked first. Additionally, the smallest standard error suggests that most sample means are similar to the population mean and so the sample is likely to be an accurate reflection of the population.

6. CONCLUSION

Energy economic and environmentally conscious operation of hydrothermal power system offers tough challenges, hence the HTS problem is formulated as bi-objective framework and normalized price penalty approach has been applied to convert this into single objective optimization problem. Then an artificial bee colony algorithm was employed and optimum generation schedule have been obtained in order to meet the energy demand while considering CEEPE scheduling simultaneously. Moreover, complicated hydraulic and electric system constraints were handled effectively which means that the available water resources have been fully utilized in order to minimize energy cost of thermal plant consequently pollutant emission reduces considerable amount. The comparison of numerical results and trade-off curve shows that the algorithm provides a competitive performance in distribution of true front. Further, statistical analysis has confirmed the performance of ABC algorithm as it holds first rank among listed literature while CEEPE scheduling. Therefore, it can be concluded that ABC has the potential to produce highly optimal hydrothermal schedule in more efficient manner without premature convergence, offers not only considerable savings in energy cost but also huge reduction in pollutant emission release

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