Application of Whale Optimization Algorithm for Environmental Constrained Economic Dispatch of Fixed Head Hydro-Wind-Thermal Power System

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Abstract*: *This work applies whale optimization algorithm for emission constrained economic dispatch of hydrothermal units including wind power. As the wind power has a characteristic of cleanliness and is renewable, this is convincing to include this for better operation of electric power system keeping in view both economic and environmental aspects. Hydrothermal scheduling integrated with wind power establishes a multi-objective problem that becomes economic emission hydro-thermal-wind scheduling problem while taking into consideration the cost due to wind uncertainty. Whale optimization algorithm is proposed to solve this emission constrained economic dispatch problem with competing objectives. This algorithm is recently developed and gives the best solution among other nature inspired algorithms. The objectives minimum generations as well as emission cost, both are optimized together including different constraints. A daily scheduling of all the three types of systems - hydro, thermal and wind is considered to evaluate the competency of this optimization technique to get a solution for this multi-objective problem. The experiments are carried out on two systems for determining the effectiveness of the suggested method. Besides, results found using the whale optimization technique have been compared with the results obtained from other evolutionary methods. From the comparison, it is experimentally justified that the whale optimization works faster and the cost of generation as well as cost of emission are lower than the other approaches.

Keywords: Economic environmental dispatch , multi-objective optimization whale optimization algorithm, water discharge rate, wind energy.

I. INTRODUCTION

In the present scenario, due to increase in power demand and corresponding fuel cost, including increase in pollution rate, it is essential to optimize economic dispatch of hydro-thermal power system. It has also become very much demanding to tackle atmospheric pollution due to fossil fuel plants. The society wants cheap and reliable electric supply with minimum level of pollution. The power plant pollution contributes to global warming which has become a concern for everyone [1].

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The optimal hydro-thermal scheduling problem has been undertaken and being solved since a long time [2]. Now attention has been drawn towards minimizing fuel cost and emission level. The present-day power system having hydro-thermal and wind power, attempts are made lessen the fuel cost and pollution level with satisfying various constraints for the three types of plants. Since wind power has gain importance in recent years it has become essential to solve economic emission dispatch of a hydro-thermal-wind system.

Many researchers have applied different soft computing methods for solving economic emission dispatch (EED) problem, such as dynamic programming [3], differential evolution [4,5], particle swarm optimization [6,7]. All the above methods can be applied to solve successfully hydrothermal scheduling problem. In these methods only generation cost is minimized, as a single objective. In the present situation, it is essential to consider minimization of pollution by emission. Pollution control as well as cost reduction are required to be considered for any practical engineering problem such as hydro-thermal-wind system considered in this paper. Many scholars in past few years have modelled this multi-objective hydrothermal scheduling problem using different techniques such as quadratic approximation–based Differential evolution [8], Improved PSO [9], NSGA-II [10] and multi-objective PSO [11]. A selection operator is introduced into differential evolution by M. Basu [12] to achieve complete solution.

Wind power is a clean and renewable source of energy. For this the operating cost is very less with reduced emission. The wind speed depends on uncertain weather condition resulting in representing wind speed distribution by probability distribution function (PDF). Weibull distribution is normally used to represent wind power [13]. Many researchers have suggested various techniques to represent the stochastic nature of wind power [14, 15]. The cost of operation of wind power and its benefit was not considered in the analysis. The additional operational cost due to wind power uncertainty has been suggested [16]. The excess cost of the system for overestimation and underestimation of wind power was calculated in [17]. System meets load demand out of spinning reserve when the output of wind plant is lower than the estimated. Alternatively, when wind power is more than the estimated the system compensates it.

GSA was solved multi-objective economic emission dispatch successfully in case of combined thermal and wind power [18]. The wind power-hydro-thermal scheduling has not much been reported. Xiaohui et al. [19] applied standard NSGA-III and introduced the dominance relationship criterion based on constrained violation. Jaya algorithm was demonstrated for better result by applying MPSO [20].

Whale optimization algorithm (WOA) was proposed in 2016 [21]. This algorithm illustrates a simple form about the hunting process of the humpback whales. WOA has many advantages over other swarm optimization algorithms. These are i) speed of convergence is high and ii) Number of parameters required for design is less in number. Currently this has been applied successfully to different mathematical problems for optimization. For design optimization, this was also implemented to many engineering problems. Haider Touma [22] applied WOA to study economic dispatch problem on IEEE 30 bus system and produced optimal or near optimal solutions. Trivedi et al. [23] applied WOA to hydrothermal system including combined economic emission dispatch. The results are found to be better when compared with that of Gradient method (GM), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO). In [24], WOA is executed to get the solution of economic dispatch problem with a system of six generating units, and found improved results. However, the effectiveness of this is not verified for the solution of scheduling problem of power system.

In the current work, WOA is implemented to solve multi-objective short-term hydro-thermal-wind scheduling (MO-STHTWS) problem while considering hydro plants with fixed head. The curves for water discharge rate of hydro power plants are modelled as a quadratic function generation of the hydro power. The additional wind power cost caused due to unpredictability characteristics of wind is estimated for the calculation of operating cost of the system. The model considers different constraints which are necessarily related to operating parameters that represent the available power plants for dispatch. The total scheduling interval is divided into different subintervals and the load demand for each subinterval is constant. The proposed technique is applied to a test system for validation. The results found are compared with the results obtained by implementing RCGA, NSGA II and SPEA 2, and it is concluded that the proposed technique is successfully implemented to get reduced fuel cost and improved emission.

The remaining part of the paper is arranged in this manner: Section 2 explains the model of proposed approach. Section 3 derives the cost of wind power. Section 4 explains the generation levels of slack generator. Section 5 and Section 6 explains about basic concepts and principles of Multi-objective optimization problem. Section 7 and Section 8 provides the brief concept and specific steps to implement WOA for solving the proposed approach. Section 9 explains the simulations and results. Section 10 explains the conclusions of the proposed research work.

II. PROBLEM STATEMENT

The proposed problem is implemented to reduce cost and emission both which is described as given below.

A Objectives

a) Generation cost of thermal power

Total generation cost is equal to generation cost of Hydro thermal unit and Wind Power unit which is written as follows:

$$Min\ f_T = \sum_{t=1}^{T}\sum_{i=1}^{N_s}[f_{it}(P_{sit})] + \sum_{k=1}^{N_w} f_{wkt}(P_{wkt})] \quad (1)$$

Where, f_T denotes operating cost of both thermal & wind generator, N_s is the total no of thermal generators , N_w is the total no of wind generators.

The total fuel cost 'f_1 'is mathematically expressed as:

$$f_1 = \sum_{m=1}^{M}\sum_{i=1}^{N_s} t_m\left[a_{si} + b_{si}P_{sim} + c_{si}P_{sim}^2 + \left(d_{si} \times \sin\left[e_{si} \times \left(P_{si}^{min} - P_{sim}\right)\right]\right)\right] \quad (2)$$

Where, a_{si}, b_{si}, c_{si}, d_{si}, e_{si} are the coefficients for cost of the i^{th} thermal unit, P_{sim} is the real power of i^{th} thermal generator n the subinterval, P_{si}^{min} denotes lower generation limit and t_m denotes time span of subinterval m.

b) Emission

The cost of fossil fuel for proposed approach is expressed as follows:

$$f_2 = \sum_{m=1}^{M}\sum_{i=1}^{N_s} t_m\left[\alpha_{si} + \beta_{si}P_{sim} + \gamma_{si}P_{sim}^2 + \eta_{si}\exp(\delta_{si}P_{sim})\right] \quad (3)$$

Where, α_{si} , β_{si} , γ_{si} , η_{si} , δ_{si} are the coefficients for emission of i^{th} thermal generator .

This is subjected to the following constraints.

a) Power balance constraints:

$$\sum_{i=1}^{N_s} P_{sim} + \sum_{j=1}^{N_h} P_{hjm} - P_{Dm} - P_{Lm} = 0, m \in M \quad (4)$$

$$P_{Lm} = \sum_{l=1}^{N_h+N_s}\sum_{r=1}^{N_h+N_s} P_{lm}B_{lr}P_{rm}, m \in M \quad (5)$$

Where, P_{hjm} is output real power of the j^{th} hydro unit, P_{Dm} represents load demand and P_{Lm} is transmission loss in the subinterval m. B_{lr} is the loss coefficients.

b) Constraints for Water availability:

$$\sum_{m=1}^{M} t_m\left(a_{0hj} + a_{1hj}P_{hjm} + a_{2hj}P_{hjm}^2\right) - W_{hj} = 0, j \in N_h \quad (6)$$

Where, a_{0hj}, a_{1hj}, and a_{2hj} denotes the coefficients for water discharge rate function,

W_{hj} denotes available water for generation by j^{th} hydro unit in the scheduling time interval.

c) Limits of Generation:

$$P_{hj}^{min} \leq P_{hjm} \leq P_{hj}^{max} \quad , j \in N_h \quad m \in M \tag{7}$$

Where, P_{hj}^{min} , P_{hj}^{max} are lower generation & upper generation limit of j^{th} hydro unit.

$$P_{si}^{min} \leq P_{sim} \leq P_{si}^{max}, i \in N_s, m \in M \quad (8)$$

and P_{si}^{max} is upper generation limit of i^{th} thermal unit.

d) Wind plant power output limits

$$0 \leq w_m^t \leq w_{R,m} \qquad (9)$$

Where $w_{R,m}$ indicates rated output power of wind power unit m.

e) Limits for reservoir storage volume

$$v_j^{min} \leq v_j^t \leq v_j^{max} \qquad (10)$$

Where, V_j^{min} is the minimum and V_j^{max} is the maximum storage volumes respectively of reservoir 'j'.

f) Limits of Water discharge

$$Q_j^{min} \leq Q_j^t \leq Q_j^{max} \qquad (11)$$

Where, Q_j^{min} and Q_j^{max} are the lowest and highest water discharge of hydro power unit respectively.

III. CHARACTERISTIC MODEL OF WIND POWER:

The power generated from wind plant is very difficult to integrate with power grid. According to Weibull distribution, the cumulative distribution function is explained as given in [19].

$$F_V(v) = 1 - \exp\left(-\left(\frac{v}{c}\right)^k\right)(v > 0) \tag{12}$$

where c: Radio factor, k: Scale Factor and the values of c and k are greater than 0, *v* is the speed of wind and *V* is the random variable of wind speed.

A. *Probability Distribution Function (PDF):*

According to cumulative distribution function (CDF), PDF of *V* is obtained as:

$$F_V(v) = \frac{k}{c}\left(\left(\frac{v}{c}\right)^{(k-1)}\right) exp\left(-\left(\frac{v}{c}\right)^k\right) \tag{13}$$

The power output of wind unit and velocity of wind are related, and this is expressed as:

$$W = \begin{cases} 0 & (v < v_{in} \text{ or } v > v_{out}) \\ \frac{w_R(v - v_{in})}{v_R - v_{in}} & ((v_{in} \leq v < v_R)) \\ w_R & (v_R \leq v < v_{out}) \end{cases} \quad (14)$$

Where, w_R is output wind power (rated), v_R is wind speed (rated), v_{in} and v_{out} are cut-in and cut-out wind speed and 'W' is a random variable.

The PDF of wind power w is determined from Eq. (14) when wind speed strikes in the domain $v_{in} \leq v < v_R$ as follows:

$$f_w(W) = \frac{k(v_R - v_{in})}{cW_R}\left(\frac{v_{in} + (v_R - v_{in})W/w_R}{c}\right)^{(k-1)} . exp\left(-\left(\frac{(v_{in} + (v_R - v_{in})\, w/w_R}{c}\right)^k\right) \quad (15)$$

Eq. (15) represents the continuous part of distribution of wind power. The distribution of random variable is expressed as:

$$P_r(W = 0) = P_r(v < v_{in}) + P_r = 1 - exp\left(-\left(\frac{v_{IN}}{c}\right)^k\right) + exp\left(-\left(\frac{v_{OUT}}{c}\right)^k\right) \tag{16}$$

By integrating the Eq. (14) – Eq. (16), the CDF of the random Variable W can be written as:

$$F_w(w) = P_r(W \leq w)$$

$$= \begin{cases} 0 & (w < 0) \\ 1 - exp\left(-\left(\frac{v_{IN} + (v_R - v_{IN})w/w_R}{c}\right)^k + exp\left(-\left(\left(\frac{v_{OUT}}{c}\right)^k\right)\right)\right) & (0 \leq w < w_R) \\ 1 & (w \geq w_R) \end{cases}$$

(17)

$$\begin{cases} 0 & (w < 0) \\ 1 - exp\left(-\left(\frac{v_{IN} + (v_R - v_{IN})\,w/w_R}{c}\right)^k + exp\left(-\left(\left(\frac{v_{OUT}}{c}\right)^k\right)\right)\right) & (0 \leq w < w_R) \\ 1 & (w \geq w_R) \end{cases} \tag{18}$$

B. *Modeling cost of wind power:*

The aim of this proposed model is to determine the output of wind power. Wind power is uncertain during operating period, so the model should provide provision for the unwanted wind power. From the probability distribution function of wind power, the overestimation is found by using Eq. (15) and Eq. (16), we get the following:

$$\begin{aligned} E(W_m^t < w_m^t) &= w_m^t . P_r(W_m^t = 0) + \int_0^{w_m^t} (w_m^t - w) f_w(w) dw \\ &= \Bigg(w_m^t \left\{ 1 - exp\left(-\left(\frac{v_{IN}}{C}\right)^k\right) + \exp\left(-\left(\frac{v_{OUT}}{C}\right)^k\right) \right\} \\ &+ (w_R v_{IN}/(v_R - v_{IN}) + w_m^t)(exp(v_{IN}/C)^k - exp(-v_m^t/C)^k) \\ &+ (w_R C/(v_R - v_{IN}))(\Gamma[1 + 1/k, (v_{IN}/C)^k] - \Gamma[1 + 1/k, (v_m^t/C)^k]) \Bigg) \end{aligned} \tag{19}$$

Where w_m^t is scheduled output of wind unit m at time gap t and W_m^t is real wind power and it is taken as a random variable.

If the Wind Power (WP) is larger than the fixed level, it is known as under estimation. The WP is modeled for calculating the cost value and penalty factor which is expressed as:

(15)

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$$E(W_m^t > w_m^t) = (w_R - w_m^t).P_r(W_m^t = w_R) + \int_{w_R}^{w_R} (w - w_m^t) f_w(w) dw$$
$$= \Bigg((w_R - w_m^t)\left\{ exp\left(-\left(\frac{v_R}{C}\right)^k\right) - \exp\left(-\left(\frac{v_{OUT}}{C}\right)^k\right)\right\}$$
$$+ (w_R v_{IN}/(v_R - v_{IN}) + w_m^t)(exp(-v_R/C)^k - exp(-v_m^t/C)^k)$$
$$+ (w_R C/(v_R - v_{IN}))(\Gamma[1+1/k,(v_m^t/C)^k] - \Gamma[1+1/k,(v_R/C)^k]) \Bigg) \quad (20)$$

Hence, the overall cost of generation of wind power plant is found by adding the cost of both overestimation and underestimation and it is given as:

$$f_w = \sum_{t=1}^{T} \sum_{m=1}^{N_w} [\lambda_m \times E(W_m^t < w_m^t) + \xi_m \times E(W_m^t > w_m^t)] \quad (21)$$

Where f_w is complete cost of WP plant during scheduling time interval, N_w is the No of WP plants, λ_m is the reserve cost coefficient for ith wind power plant overestimation, ξ_m is the penalty cost coefficient

IV. PRINCIPLE OF MULTIOBJECTIVE OPTIMIZATION

Multi-objective optimization has a number of optimal solutions, but among this one solution is chosen because no solution is better than the other considering all the objectives. Hence, these optimization problems which consist of a number of objectives can be expressed as:

Minimize $f_i(x)$, i =1,…..,N_{obj} (22)

Subject to:

$$\begin{cases} g_k\ (x = 0) & k = 1 \dots . K \\ h_l(x) \le 0 & l = 1 \dots L \end{cases} \quad (23)$$

where f_i is i^{th} objective function, x is a decision vector.

V. WHALE OPTIMIZATION ALGORITHM OVERVIEW

The proposed algorithm [21] has recently been developed by S. Mirjalili and A. Lewis, which follows the natural behavior of humpback whales. The paragraph below gives brief information about these whales. Whales are recognized as the largest mammals among all mammals. Whales have common cells similar to those of human in different areas of their brains known as spindle cells. These cells help for judgment, and for behaving socially & emotionally like human beings but clearly with less smartness. The impressive matter about these whales is the social behavior & exceptional hunting method. This unique foraging nature is referred to as bubble net feeding method. These whales like to catch small fishes or school of krill which are close to the surface of water.

A. *Encircling Prey*

Humpback whales can know about the prey and their location. So, they surround the prey. While designing, the optimum position in the search space unknown beforehand so WOA algorithm presumes the recent best solution as its destination for its prey or assumes it to be nearer to the optimal value. When the best search operator is determined, the other search operators must try to renew their positions according to the position of best search operator.

This method is illustrated as below:

$$D = |C.X^*(t) - X(t)|$$
$$X(t+1) = X^*(t) - A.D \quad (24)$$

Where, t denotes present iteration, A , C are coefficient vectors, X* is the position vector of the best solution found, X is the position vector. X* needs to be updated in each iteration for solution updation.

The A and C vectors are computed as follows:

A = 2 a · r − a (25)

C = 2 · r (26)

where 'a' is decreased from 2 to 0 linearly for exploration and exploitation phases both, 'r' is a random vector in [0,1].

The position of the current best record (X *) is obtained. Then, the position (X) of a search operator is modified according to X *. By altering the value of vectors, A and C, places around the best operator can be obtained corresponding to their present position.

B. *Bubble-net attacking method (exploitation phase)*

For developing this model mathematically, two mechanisms are explained as followed:

1) *Shrinking encircling mechanism:*

It is to be noted that the range of 'A' is varied by decreasing the value of 'a'. So, A is a random value in the interval [−a, a]. Fixing the random values for A in [−1,1], the new position of a search operator is decided between the original position of the operator and the position of the current best operator.

2) *Spiral updating position:*

In this mechanism the distance between the whale located at (X) and prey located at (X *) is determined. A spiral equation is then developed between the position of whale and prey, which gives a helix shaped movement of these whales. This is described by the equations shown below:

$$X(t+1) = D'.e^{bl}.\cos(2\pi l) + X^*(t) \quad (27)$$

Where $D' = |X^*(t) - X(t)|$ (28)

It represents the distance between the ith whale and its prey and is considered as the best solution,

b is a constant for defining the shape of the logarithmic spiral, l is a random number in [−1, 1].

3) *Search for prey (Exploration Phase):*

In this phase, A is used with the random values greater than 1 or less than −1 to make the search operator to go away from a reference whale. The position of search operator is updated in this phase in the same way as a randomly chosen search agent unlike exploitation phase. This mechanism helps for better exploration which allows WOA algorithm to complete a global search. The mathematical model is as follows:

$$|D = (C.X_{rand} - X)\ | \quad (29)$$

$$X(t+1) = X_{rand} - A.D \quad (30)$$

Where, X $_{rand}$ is a random position vector selected from the current population (Random whale).

This algorithm begins with a set of solutions which are random. For each iteration, search operators update their positions according to a search operator which is chosen randomly or according to the best solution realized till now. The value of the parameter 'a' is 2 for exploration which is decreased to 0 to provide exploitation. When | A | > 1, a random search operator is chosen and when | A | < 1, best solution is selected to update the position of the search operators.

VI. PROPOSED ALGORITHM FOR EED

The important steps of the proposed new algorithm are defined below:

- **Step 1: Initialization**
- Number of populations is N_p, host nests is represented by $X = \left[X_1, X_2, \ldots\ldots\ldots X_{NP}\right]^T$ where each nest presents $X_i = \left\lfloor P_{i1}, P_{i2} \ldots\ldots\ldots P_{ij} \ldots\ldots\ldots P_{iN} \right\rfloor$ that implies the units of output power. The output power is initialized by $P_{ij} = P_j^{\min} + rand_1 * \left(P_j^{\max} - P_j^{\min}\right)$ where $rand_1$ is a uniformly distributed random number between 0 and 1.
- **Step 2**: Determine the Encircling prey, so that we can find bubble net feeding.
- **Step 3:** Update the spiral position and adopt for random searching process.
- **Step 4 (Stopping Criteria):** The proposed algorithm is stopped when the number of iterations becomes same as the pre-decided value.

VII. SIMULATION AND RESULTS

The algorithm is applied to two test systems. The result of the algorithm implies the effectiveness and performance of whale optimization algorithm, as well as for SPEA2 and NSGA-II for the above problem. The above method is executed in Pentium-IV, 80GB, 3.0Hz. To simplify the clashing relation among the objective function, each objective is optimized by using Real coded genetic algorithm. The parameters taken for the above algorithm are, population size, maximum no of generation, probabilities for cross over and mutation, and the values taken are 50,100,0.9 and 0.2 respectively. In case of NSGA-II and SPEA-2, maximum number of generations is taken as 50, size of population is taken as 20 and the probabilities for crossover and mutation are taken as 0.9 and 0.2 respectively.

The scaling factor and shape factor for wind power system are taken as 15 and 2.2. The value of over and under estimation cost coefficient of two wind power generator are as follows: $\lambda_1 = \lambda_2 = 310\$/(MWh)$,

$\xi_1 = \xi_2 = 100\$/MWh$

The weight violation ρ=1, ω=1.

A. Test system 1:

This system includes two units from hydro, thermal and wind. The data of transmission loss coefficients and hydro plant are taken from [2]. Both objectives are minimized separately by using RCGA; the results are given in Table-1 and 2. It is concluded that for cost minimization, fuel cost is 6.212×10^{4} and emission is 671.6144 lb but cost increases to 6.431×10^{4} and emission decreases to 572.255 lb under emission minimization.

The optimization result of both cost and emission by using WOA has given in Table-3. In this the cost of the fuel is 6.321×10^{4}, it is greater than 6.212×10^{4} and smaller than 6.431×10^{4} but in case of emission it is 616.971 lb which is smaller than 671.6144 lb and higher than 572.255 lb. Table 4and Table 5 shows the results of NSGA-II, SPEA 2. Table 6 displays the comparison result of proposed approach with other approaches. From the above result it can be concluded that implementing proposed approach less cost, reduced emission level and less computational time is obtained than other approaches.

B. Test system 2:

This system considers two hydro, four thermal, two wind power units. All data are considered from [20]. Result obtained from the minimization of cost and emission is given in Table 7 & 8. According to cost minimization, fuel cost is 65516.69 $ and emission minimization, the fuel cost increases to 89320.69$, emission decreases to 23222.11 lb. WOA is implemented to optimize cost, emission both. The optimization result of this is shown in Table 9. In this table, the fuel cost is 68333.03 $, this is more than 65516.69$, less that 89320.69$ but emission is 25278.30lb, its value is lower than 35218.44lb, greater than 23222.11lb. The results of NSGA-II, SPEA 2 are displayed in Table 10 and Table 11.

Result acquired by implementing WOA and RCGA are compared with Chiang's method [20] for all the cases i.e. reduced cost, emission and economic environmental dispatch. Table -12 displays the result acquired by Chiang's method, RCGA, suggested WOA, NSGA-II, SPEA-2. It is evident from our results that the values obtained are minimum and also it takes less CPU time. Thus, it is concluded that the suggested method is efficient in comparison to other method for solving hydrothermal wind power system.

Table 1: Results found from RCGA method for Cost minimization of test system 1

Sub interval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	Cost (10^5 $)	Emission (ton)	CPU time (second)
1	247.033	90.569	178.267	436.373	58.98	51.68	39.872			
2	309.845	164.454	228.256	562.015	54.34	43.56	69.548	6.212	671.644	18.835
3	296.587	138.632	212.699	524.751	41.08	33.76	58.675			

Table 2: Results acquired from RCGA method for emission reduction of test system 1

Subinterval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	Cost (10^5 $)	Emission (ton)	CPU time (second)
1	224.402	45.861	292.178	378.412	67.89	64.65	43.000			
2	289.844	205.562	298.468	465.117	55.89	48.45	65.837	6.431	572.255	17.263
3	317.254	135.413	296.652	414.243	51.34	34.78	58.495			

Table 3: Results obtained from proposed WOA method of test system 1

Subinterval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	Cost (10^5 $)	Emission (ton)	CPU time (second)
1	227.732	97.165	257.931	356.454	56.23	44.89	39.235			
2	306.858	164.451	270.643	527.371	48.67	37.56	69.311	6.121	616.771	22.544
3	301.745	131.956	261.517	463.648	66.34	43.78	58.898			

Table 4: Results found from proposed NSGA II method of test system 1

Subinterval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	Cost (10^5 $)	Emission (ton)	CPU time (second)
1	225.339	68.349	257.969	389.674	54.65	40.43	41.332			
2	320.944	173.657	264.524	509.379	51.77	32.65	68.421	6.632	618.480	30.864
3	289.633	149.413	257.589	460.839	43.54	28.87	57.578			

Table 5: Results obtained from proposed SPEA 2 method of test system 1

Subinterval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	Cost (10^5 $)	Emission (ton)	CPU time (second)
1	252.543	65.814	245.801	377.591	64.34	34.58	41.349			
2	316.201	174.897	270.273	507.574	54.86	30.48	68.345	6.654	619.420	32.541
3	267.635	150.029	265.119	474.582	46.68	23.83	57.715			

Table 6: Comparison results of RCGA, proposed WOA, NSGA II and SPEA 2 of test system 1

Parameter	**Minimum cost RCGA**	**Minimum emission RCGA**	**Economic Environmental Dispatch**		
			WOA	**NSGA II**	**SPEA 2**
Cost (10^5 $)	6.212	671.614	6.312	6.632	6.654
Emission (ton)	6.431	572.255	616.771	618.480	619.420
CPU time (in sec)	18.835	17.263	22.594	30.864	32.541

Table 7: Results found from RCGA for cost reduction of test system 2

Sub interval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	P_{s3} (MW)	P_{s4} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	**Cost** (10^5 **\$**)	Emission (ton**)**	CPU time (in sec)
1	225.428	376.303	23.125	30.226	124.989	139.784	38.06	23.88	19.849			
2	215.136	429.908	90.252	118.011	124.906	139.706	65.46	43.62	28.029	65516.54	35218.44	38.36
3	228.504	298.182	26.619	30.052	209.812	229.519	68.34	38.91	22.648			
4	209.824	477.329	99.014	112.725	209.876	229.548	92.76	21.52	38.326			

Table 8: Results acquired from RCGA for emission reduction of test system 2

Sub interval	P_{h1} **(**MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	P_{s3} (MW)	P_{s4} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	**Cost** (10^5 **\$**)	Emission (ton)	CPU time (in sec)
1	168.611	313.065	73.247	134.369	135.681	92.330	57.09	43.69	18.143			
2	247.361	409.251	79.078	142.317	148.404	90.968	78.03	61.42	28.212	89320.69	23222.11	41.98
3	209.708	357.862	76.854	139.314	141.917	97.148	95.06	34.88	22.838			
4	250.000	500.000	90.284	168.322	185.578	93.429	98.02	20.84	39.513			

Table 9: Results found from suggested WOA method for test system 2

Sub interval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	P_{s3} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_{s4} (MW)	P_L (MW)	**Cost** (10^5 **\$**)	Emission (ton)	CPU time (in sec)
1	196.525	346.840	93.607	110.069	121.624	87.77	48.54	50.220	18.9642			
2	189.205	459.634	98.504	117.132	123.504	94.87	37.55	140.401	28.4850	68333.03	25278.30	32.42
3	49.842	297.161	97.615	113.182	124.326	114.76	31.81	139.871	22.0356			
4	241.232	475.142	98.716	173.588	211.027	126.65	26.84	139.171	38.933			

Table 10: Results obtained from proposed NSGA II method of test system 2

Sub interval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	P_{s3} (MW)	P_{s4} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	**Cost** (10^5 **\$**)	**Emission (ton)**	CPU time (in sec)
1	202.063	364.211	20.000	112.529	124.303	50.161	97.88	76.22	20.113			
2	245.567	380.097	99.584	175.000	125.452	139.711	132.66	43.77	27.054	68388.19	25759.32	44.76
3	186.788	376.160	98.524	112.650	124.775	140.021	145.54	36.94	22.558			
4	242.798	467.927	97.112	175.000	210.185	139.417	127.86	28.74	38.855			

Table 11: Results found from suggested SPEA 2 technique for test system 2

Sub interval	P_{h1} (MW)	P_{h2} (MW)	P_{s1} (MW)	P_{s2} (MW)	P_{s3} (MW)	P_{s4} (MW)	Pw_1 (MW)	P_{w2} (MW)	P_L (MW)	Cost (10^5 $)	Emission (ton)	CPU time (in sec)
1	203.908	390.266	20.358	116.936	118.675	69.871	102.45	83.96	19.849			
2	214.876	367.122	99.278	113.012	210.038	89.033	121.65	68.71	28.029	68392.39	26005.75	51.026
3	233.847	342.552	120.537	112.318	137.511	137.734	173.85	51.03	22.648			
4	225.971	485.404	120.386	168.313	206.749	140.432	206.73	43.05	38.346			

Table 12: Comparison of results of RCGA, suggested WOA, NSGA II and SPEA 2 for test system 2.

Parameter	**Minimum cost RCGA**	**Minimum emission RCGA**	**Economic environmental dispatch** WOA	NSGA II	SPEA 2
Cost (10^5 $)	65516.54	89320.69	68333.03	68388.19	68392.39
Emission (ton)	35218.44	23222.11	25278.30	25759.32	26005.75
CPU time (in sec)	21.6385	20.2763	32.42	44.76	51.026

VIII. CONCLUSION

Whale optimization algorithm is applied in the system to solve the problem of economic emission dispatch. Fixed head hydro generating units has been considered which also includes thermal and wind generation systems. The two objectives of this problem are minimum fuel cost and at the same time minimum emission. The problem is formulated as a multi-objective optimization problem. A daily scheduling problem of a mixed kind of system is taken. For testing purpose, two plants are considered from each type. All plants are taken in cascaded form. This mixed system is tested to verify the performance of WOA. The results obtained from the proposed WOA are compared with RCGA, SPEA and NSGA II. The numerical results obtained from the comparison shows that the value of fuel cost and cost of emission are minimum for the proposed method. It is also verified from the results that very less CPU time is required for this method as compared to other methods. Hence, the proposed WOA method provides a more robust and efficient technique to solve the EED problem.

REFERENCES

1. IEEE Current Operating Problems Working group, Potential impacts of clean air regulations on system operations, IEEE Trans. Power Syst. 10 (1995),647-653.
2. M. Basu, Economic environmental dispatch of fixed head hydrothermal power systems using Non-dominated sorting genetic algorithm II. Elect. Power Syst., Appl. Soft Computing. 11 (2011) 3046-3055
3. Rebennack S, Flach B, Pereira MVF,and et.al., Stochastic hydro-thermal scheduling under emissions constraints. IEEE Trans Power Syst 2012; 27(1):58–68.
4. Yuan X, Wang L, Yuan Y, et al. A modified differential evolution approach for dynamic economic dispatch with valve-point effects. Energy Conversion and Management 2008; 49(12):3447–53.
5. Yuan X, Cao B,Yang B, et al. Hydrothermal scheduling using chaotic hybrid differential evolution. Energy Conversion and Management 2008;49(12):3627–33.
6. Yuan X, Su A, Yuan Y, et al. An improved PSO for dynamic load dispatch of generators with valve-point effects. Energy 2009; 34(1):67–74.
7. Yuan X, Su A, Yuan Y, et al. Non-convex dynamic dispatch of generators with prohibited operating zones. Opt Control Appl Methods 2009;30(1):103–20.
8. Lu S, Sun C. Quadratic approximation based differential evolution with valuable trade off approach for bi-objective short-term hydrothermal scheduling. Expert Syst Appl 2011; 38(11):13950–60.
9. Lu S, Sun C, Lu Z. An improved quantum-behaved particle swarm optimization method for short-term combined economic emission hydrothermal scheduling. Energy Conversion Management 2010;51(3):561–71.
10. Deb K, Pratap A, Agarwal S, Meyarivan T. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans Evol Comput 2002; 6:182–97.
11. Basu M. Economic environmental dispatch of hydrothermal power system. Int J Electr Power Energy Syst 2010; 32(6):711–20.
12. Islam MR, Saidur R, Rahim NA. Assessment of wind energy potentiality at Kudat and Labuan, Malaysia using Weibull distribution function. Energy 2011;36(2):985–92.
13. Zhou W, Peng Y, Sun H. Optimal wind–thermal coordination dispatch based on risk reserve constraints. Eur Trans Electr Power 2011; 21(1):740–56.
14. Yuan X, Ji B, Zhang S, et al. An improved artificial physical optimization algorithm for dynamic dispatch of generators with valve-point effects and wind power. Energy. Convers Manage 2014; 82:92–105.
15. Hetzer J, Yu DC, Bhattarai K. An economic dispatch model incorporating wind power. IEEE Trans. Energy Conversion 2008;23(2):603–11.

16. Mondal S, Bhattacharya A. Multi-objective economic emission load dispatch solution using Gravitational search algorithm and considering wind power penetration. Int J Electr Power Energy Syst 2013; 44(1):282–92.
17. Yuan, X.,Tian, H.,Yuan, Y., et al. An extended NSGA-III for solution multi-objective hydrothermal- wind scheduling considering wind power cost. Energy Conversion & Management, 2015, 96 568-578.
18. Suresh K. Damodaran, and T. K. Sunil Kumar, Hydro-Thermal-Wind Generation Scheduling Considering Economic and Environmental Factors Using Heuristic Algorithms, Energies, MDPI, 2018.
19. Hari Mohan Dubey, Ant lion optimization for short-term wind integrated hydro-thermal power generation scheduling. Electrical power and energy systems 83(2016) 158-174.
20. Jianzhong Zhou, Peng Lu., Short-term hydro-thermal-wind complementary scheduling considering uncertainty of wind power using an enhanced multi-objective bee colony optimization algorithm. Energy Conversion and Management 123 (2016) 116–129.
21. Seyedali Mirjalili, Andrew Lewis. The Whale Optimization algorithm. Advances in engineering software 95 (2016) 51-67.
22. Haider J. Touma, Study of The Economic Dispatch Problem on IEEE 30-Bus System using Whale Optimization Algorithm. International Journal of Engineering Technology and Sciences (IJETS), Vol. 5(1).
23. Indrajit N. Trivedi, Motilal Bhoye, An Emission Constraint Environment Dispatch Problem Solution with Microgrid using Whale Optimization Algorithm, IEEE, 2016 National Power Systems Conference (NPSC).
24. Adarsh Vijayan pillai1, S. K. Nandakumar et al., Economic Dispatch problem using whale optimization algorithm., International Journal of Pure and Applied Mathematics Volume 117, No. 22 2017, 253-257

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