Multi Objective Generation Dispatch of a Hybrid System with Fuzzy based Space Search Algorithm

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Abstract: This paper presents a new approach to the solution of optimal power generation for economic emission load dispatch (EELD) using space search algorithm to a hybrid power system. The proposed space search algorithm (SSA) has been applied on 23 benchmark test functions and the results were compared with Gravitational search algorithm (GSA), Particle swarm optimization (PSO), Differential evolution (DE) and Grey wolf optimizer (GWO). The results show that SSA method is able to provide very competitive results compared to other established meta-heuristics. After that, the economy objective function is minimized, followed by minimization of emission level objective function. Then, both the objectives are combined through a fuzzy coordination method to form a fuzzy decision making (FDM) function. Maximizing the FDM function then solves the original two-objective problem. The minimization and maximization tasks of this optimization problem are solved by the space search algorithm. The optimisation technique was applied to the hybrid system and a conventional power system with only three conventional thermal generators. The results by hybrid system provide cheaper generation schedule in comparison to individual system of thermal generators.

Keywords: Economic Emission Load Dispatch; Space Search Algorithm; Fuzzy Decision Making; Two-Objective Problem; Hybrid System

1. Introduction

The economic emission load dispatch problem is a complex nonlinear constrained optimization problem, which is to allocate optimal amount of generated power for the fossil based generating units in the system by minimizing the fuel cost and emission level simultaneously, subject to system constraints. With growing demands, the production of more energy has led to larger scale of pollution. So, the prime objective in scheduling the thermal generators will be to reduce the fuel cost which results in profit and also saving the natural resources. Thermal energy, though an efficient and easily harnessed energy source, causes a wide spread pollution to natural resources like soil, air and water. An alternative to remove dependency on thermal power plant to meet the load demand will be helpful. Moreover, renewable energy sources cannot meet the load demand independently due to limitations in harnessing. A mix in generation by using hybrid systems, i.e. a mixture of renewable energy sources and conventional thermal power plants can solve both the problems.

The author John Hetzer et al. [1] has proposed to include the wind energy conversion system (WECS) generators in the economic dispatch problem. In this paper he has included the overestimation and underestimation penalty factors to the wind farms in the classic dispatch factors. Edgardo D. Castronuovo et al. [2] have proposed the utilization of water storage ability to improve wind park operational economic gains and to attenuate the active power output variations due to intermittence of the wind-energy resource. The stochastic characteristics of the wind power are exploited in the approach developed in order to obtain a recommended operational condition. J Garcia-Gonzalez et al. [3] have proposed the use of hydro-pumped storage units as a good complement to wind generation due to their ability to manage positive and negative energy imbalances over time. The problem is formulated by taking two random

parameters: market price and wind generation. V.S. Pappala et al. [4] have addressed a multistage stochastic model for the optimal operation of wind farm, pumped storage and thermal power plants. In this paper the output of wind farm and the electrical demand are considered as two independent stochastic processes. Eleanor Denny et al. [5] have tried to reduce the emission levels by the use of wind energy. They have developed a dispatch model to analyze the impact of wind generation on the operation of conventional plants and emission of CO₂, SO₂ and NO_x. A.T. Al-Awami et al. [6] have formulated a dispatch solution with wind and thermal units taking into account the stochastic nature of wind power output and the imbalances charges due to the mismatch between the actual and scheduled wind power outputs. They have proposed an enhanced multi-objective particle swarm optimization to search for the set of Pareto-optimal solutions that is the best compromising solution for least emission and best cost. This proposed technique has been helpful for the system operators to operate the grid with high penetration of wind power more efficiently while maintaining emissions within restricted limit. In another paper, V. Miranda et al. [7] have successfully developed an economic dispatch model with fuzzy wind constraints and attitudes of dispatchers. Tzyy_Chyan Lu et al. [8] have proposed an optimization method combined with Evolutionary space search algorithm (ESSA). The main aim of ESSA is to divide the feasible solution space into many subspaces and search for the solution by finding the optimal subspaces. These process increases the probability of selecting subspaces that generates better fitness. To find out the best subspace combination effectively and prevent premature convergence, an overlapping strategy is proposed to encode subspace. In concluding the paper ESSA searches the optimal solution by finding correct subspaces. W. Huang et al. [9] reported the potential of space search optimization with accelerated convergence strategies. S. Papaefthimiou et al. [10] have proposed the use of Pumped storage as the most suitable storage technology for achieving high wind penetration levels in multi-MW sized autonomous island grids, where the technical constraints introduced by the conventional generating units impose limitations on the output of wind farms. In this paper they have proposed an operating policy for hybrid wind-hydro power stations in island grids, in order to increase wind penetration. M. Tripathy et al. [11] have applied Bacteria foraging optimization to probabilistic wind model in economic load dispatch problem. Warsono et al. [12] have reported the genetic algorithm based approach to model the intermittent resources as negative load. To the best of the authors knowledge, this new space search algorithm is hardly applied to engineering problems. To validate the proposed method, it has been applied to 23 standard benchmark functions [13-22]. Then, the results obtained from Space search algorithm (SSA) method outperform when compared with Gravitational search algorithm (GSA) and Grey wolf optimizer (GWO) in almost all cases. The current research is focused at usage of renewable energy in existing power grids and optimizing grid objectives such as cost, reliability, environmental impact, customer preferences, etc. Here a hybrid model has been formulated for economic emission dispatch of the system with a wind farm, a pumped storage unit and three conventional thermal power plants by using the proposed space search algorithm.

2. The Hybrid System

The hybrid system comprises of three conventional thermal generators, a wind generator and also a pumped storage plant. In the proposed hybrid system, three prime objectives are met which follows as minimization of cost, minimization of emission and best compromised solution of cost and emission.

A. Wind power units

The wind power penetration to a system is modelled in two ways. The first one is the probabilistic wind turbine cost model and another is the negative load model. A probabilistic model for the wind turbine output based on the Weibull probability density function accounts for both overestimation and underestimation of available wind power [11]. In the negative load

model all the forecasted wind power will be used to calculate the new load by subtracting the wind power from the total load [12].

Wind power is clean source and after initial fixed cost it has practically less operating cost. The wind power being dependent on speed and direction of wind, so is the power contributed to the hybrid system. Here, the Wind Energy Conversion System (WECS) output is used to transform wind speed to the power output considering the wind farm as a single unit. The wind power output is obtained from the predicted wind speed as follows.

$$Pw(t) = 0 \text{ for } V(t) \geq V_{co} \text{ or } V(t) < V_{ci} \quad (1)$$

$$Pw(t) = P_r * \frac{[V(t) - V_{ci}]}{[V_r - V_{ci}]} \text{ for } V_{ci} \leq V(t) < V_r \quad (2)$$

$$Pw(t) = P_r \text{ for } V_r \leq V(t) < V_{co} \quad (3)$$

Thus, it is seen that power is generated only within cut in and cut out speed.

Due to the stochastic nature of wind, wind farms are imposed with overestimation and underestimation penalty factors. If a certain amount of wind power is assumed and that power is not available at the assumed time, power must be purchased from an alternate source or loads must be shed. So, a penalty called as overestimation penalty has to be imposed on the farm. If the available wind power is actually more than what was assumed, then dummy load resistor need to be connected to waste the surplus power resulting in underestimation penalty. For simplicity, the negative load model is used in the present study for solving the economic emission dispatch problem. The coordinated operation of Pumped storage plant and daily wind power availability provides significant generation during scheduled period and ensuring positive generation (generator) or negative generation (motoring). To meet the load demand, the remaining power is produced by thermal plants in a hybrid system

B. Pumped storage unit

It is a hydro plant with a head and tail reservoir. During peak hour the turbine drives the generator and the plant generates electrical energy while during off peak hours the generator operates as a motor and drives the turbine which now works as a pump raising the water from the tail water reservoir to the head water reservoir, thereby reducing the capital cost of the plant and improving the operating efficiency.

The daily operation of pumped storage is modeled as follows:-

Generating mode

$$PL_{t+1} = PL_t - M * PG_t / \eta_g \quad (4)$$

Pumping mode

$$PL_{t+1} = PL_t + M * PP_t * \eta_p \quad (5)$$

$$PG_{Min,t} \leq PG_t \leq \text{Min}(PD_{Max,t}, \eta_g * PL_t / M) \quad (6)$$

$$PP_{Min,t} \leq PP_t \leq PP_{max,t} \quad (7)$$

$$PL_{Min,t} \leq PL_t \leq PL_{max,t} \quad (8)$$

Pumped storage hydro has provided significant benefits to our energy supply system including storage, load balancing, frequency control, resource generation.

The advantages of pumped storage plant in hybrid system are given below.

- Rapid response to offset wind generator variability.
- Store wind energy during off-peak periods of load demand.
- Prevent wind curtailment and avoid new transmission on investments.
- “Shape” prices by optimizing schedules of wind generator output and storage.
- Allows for better integration of renewable energy into the power grid.

The disadvantages of pumped storage plant in hybrid system are given below.

- Capital and operating costs of the combined wind and pumped storage is complex.
- Energy losses (about 25%) related to pumped storage.

C. Combined operation of wind farm and pumped storage unit

During high wind power generation, the pumped storage unit works as motor and lifts the water to the upper reservoir and use it when the demand on system increases or when the wind power generation is lower than the predicted value. The combination has certain advantages like the combination produces a constant output irrespective of wind speed, removing the problems of overestimation or underestimation penalty factors on wind farms and ensuring a higher minimum power delivery to the grid. As the power output of wind power plant depends upon the velocity and direction of wind hence, it becomes stochastic in nature. The output of wind plant in this case varies from 10 MW to 45 MW. In this hybrid system a base power of 30 MW is selected from wind plant to meet the load demand. When wind generation exceeds the base power of 30 MW, it is assumed as over generation and we go for energy storage as in pumped storage power plant, i.e., the water is pumped from lower reservoir to upper reservoir by the motoring mode. Whenever, wind power is less than 30 MW and then the pumped storage plant generates power in generating mode. In this way both the plants are operated in a coordinated way to level the load balance of the hybrid system and enhancing the efficiency of system by saving energy.

D. Thermal units

In thermal power plant the steam produced by boilers utilizing heat from combustion of fossil fuels is used to drive the Turbo-generator set to produce electrical power. The fuel cost function of each unit considering the valve-point effects is expressed as the sum of a quadratic and a sinusoidal function. The total fuel cost in terms of real power output can be expressed as:

$$OC(P_i) = a_i + b_i * P_i + c_i * P_i^2 + abs[d_i * \{\sin(e_i * (PG_{Min,i} - P_i))\}] \quad (9)$$

Where a_i , b_i , c_i , d_i and e_i are the cost coefficients of the i^{th} thermal unit.

Mainly, three polluting gases are released from the thermal power plants viz. CO_2 , SO_2 and NO_X . Considering the thermal plants the major source of emission is NO_X and accordingly this study is focused on the emission of NO_X . The total emission in the system is expressed as:

$$Emc(P_i) = \gamma_i + \beta_i * P_i + \alpha_i * P_i^2 + \eta_i * \{\exp(k_i * P_i)\} \quad (10)$$

Where, γ_i , β_i , α_i , η_i and k_i are the emission coefficients of the i^{th} thermal unit.

3. Problem Formulation

In the problem formulation of economic emission generation dispatch, three prime objectives are met which follows as: (a) Economic dispatch, (b) Least emission dispatch and (c) Economic and least emission dispatch.

A. Economic dispatch

Economic dispatch deals with the minimization of cost of power production is primarily targeting to find the optimal allocation of the electrical power output from various available generators with given constraints. These constraints typically take the form of minimum and maximum generator outputs. Here, the objective function is the minimization of the cost.

$$J_1 = \text{Min} \sum_{i=1}^n OC(P_i) \quad (11)$$

B. Least emission dispatch

The total amount emission level from all the units in the system can be expressed as:

$$J_2 = \text{Min} \sum_{i=1}^n Emc(P_i) \quad (12)$$

C. Economic and least emission dispatch

Since, J_1 and J_2 are dependent on one another it is better to minimize them independently to get the trade off curve. Both the objectives J_1 (cost) and J_2 (Emission) are conflicting in nature. Fuzzy logic is considered to be very suitable to address the combined objectives J_3 satisfactorily. The approach in this case is to find the best compromised solution from the possible set of solutions, considering the two objectives simultaneously with the help of fuzzy logic coordination method.

$$J_3 = \text{Min} \sum_{i=1}^n \{OC(P_i) + CF * Emc(P_i)\} \quad (13)$$

4. Space Search Algorithm

The algorithm is used to find the most optimal allocation of the generation schedule for all the three objective functions by search space algorithm. In this algorithm, the whole search space is divided into many subspaces and search for the solution by finding the optimal space. According to fitness value in each generation the subspaces areas are selected. This process increases the probability of selecting subspaces that generates better fitness and enables the algorithm to exploit good subspaces. The probability of getting trapped by local optima is less as the reduction of search space from generation to generation. The algorithm randomly searches in each search space (local search) and then the other search spaces to find the optimal search space. The complementary search space of each search space (global search space) is calculated [9]. The position of maximum and minimum objective function value decides the boundary of next search space (reduced). The point of solution becomes closer and closer to global optimum as the search space is gradually reduced in successive generations.

Figure 1. A concept of reduced search space developed in successive generations

This figure 1 indicates a process of traversing the search space of the proposed algorithm in successive iterations. The current solution is constantly updated by new solutions (generation of new offspring). During generations of new solutions, the search space based on current solutions becomes smaller and smaller. The refinement solution takes place till the last generation. Then the current solutions are converged to same global optimum and corresponding search space squeezes to a single point. So, all the solutions in the current population have the same fitness. The method terminates after a predefined maximum number of generations is reached.

The flow chart of the proposed algorithm is shown in figure. 2. This algorithm is given below in details by the following steps.

A. Algorithm Procedure

Sample solutions are randomly generated with uniform distribution over the whole space. No of samples are predefined.

Step 1. After initialization, the value of the objective function is determined for each sample solutions.

Step 2. Position of the maximum and minimum values of the objective function is noted. This position becomes the boundary of the next search space (local search).

Step 3. The next search space is reduced as the boundary restricts the value in it. Now again sample solutions are randomly generated with uniform distribution in the complementary reduced space (global search space).

Step 4. To rule out the possibly of the local optimum point, position of the maximum and minimum values of the objective function is noted again in the complementary space (global search space).

Step 5. The position of maxima and minima that we get in step 3) and in step 5) is compared. Whichever is the true minima and maxima, that space is chosen as next reduced sample space.

Step 6. Steps from 2) to 6) are repeated till finally getting the maximum and minimum values as same. The sample space then reduces to a point. The details about the algorithm are given in reference [8], [9].

The mathematical details, procedure of local search and global search and pseudo code of space search algorithm are clearly described in reference [9].

B. Best compromise solution

The fuzzy set theory has been implemented to derive efficiently a solution from the set of non-dominated solutions. The fuzzy decision making function is represented by the membership function to replace each variable as a precise value. Figure. 3 depicts the membership function μ_c for the fuzzy variable signifying total fuel cost $f_i(PG_i)$. The decision maker is fully satisfied with the cost if, $\mu_c = 1$, and not satisfied at all if $\mu_c = 0$. Therefore, the value of membership function indicates the adaptability of the economy index. Due to the imprecise nature of decision maker's judgment, the i^{th} objective function of a solution in the non-dominated set $f_i(PG_i)$ is represented by a membership function $\mu_i(PG_i)$ defined as:

$$\mu_i(PG_i) = \frac{\{f_i^{\max} - f_i(PG_i)\}}{\{f_i^{\max} - f_i^{\min}\}} \quad (14)$$

Where, $f_i^{\max}$ and $f_i^{\min}$ are the maximum and minimum values of i^{th} objective, respectively.

Then the fuzzy decision making function (FDM) is described as:

$$FDM_i(PG_i) = \begin{cases} 0 & \text{for } \mu_i(PG_i) \leq 0 \\ \mu_i(PG_i) & \text{for } 0 < \mu_i(PG_i) < 1 \\ 1 & \text{for } \mu_i(PG_i) \geq 1 \end{cases} \quad (15)$$

For each non-dominated solution k, the normalized membership function is known as fuzzy decision making function (FDM^k) which is given below.

$$FDM^k = \frac{\sum_{i=1}^2 FDM_i^k(PG_i)}{\sum_{j=1}^M \sum_{i=1}^2 FDM_i^j} \quad (16)$$

The best compromising solution of EELD problem is the one having the maximum value of FDM^k as fuzzy decision making function. Where, M is the total number of non-dominated solutions. Then all the solutions are arranged in descending order according to their membership function values which will guide the decision makers with a priority list of non-dominated solutions in view of the current operating conditions.

Figure 2. Flow chart of the proposed space search algorithm

Figure 3. Membership function of fuzzy fuel cost

C. Application of space search algorithm

The results are provided in next section when space search algorithm is applied for scheduling three conventional thermal generators. In each of iteration, the maximum limit is reduced and minimum limit is raised so that the space to be searched for the scheduling is reduced. This process continues till we arrive at a point where the maximum and minimum limit is the same. So, we find that with each of iteration the net space to be searched is being reduced. When the maximum limit and minimum limit nearly coincide we find that the space to be searched has been reduced to a point and that position is the optimized solution schedule.

5. Results and Discussion

A. Benchmark functions

The proposed space search algorithm (SSA) as well as gravitational search algorithm (GSA), PSO, DE and grey wolf optimization (GWO) have been applied to 23 standard benchmark functions to evaluate their performances. Three types of functions are experimented in this study and are reported in Tables 1-3. Table 1 represents the unimodal benchmark functions with functions F_1 to F_7 , the multimodal benchmark functions F_8 to F_{13} are provided in Table 2 and the fixed dimension multimodal functions F_{14} to F_{23} are also provided in Table 3. The above mentioned three heuristic methods have been applied to these minimization test functions and their results are compared. In all these cases, the population size is set to 50, dimension is 30 and maximum number of iterations is 500 for functions of Tables 1, 2 and 3. The result obtained by SSA method is averaged over 30 runs and the average value and the standard deviation of unimodal functions F_1 to F_7 are compared with DE, PSO, GSA and GWO [22] methods and reported in Table 4.

Similarly, the average value and standard deviation of multimodal test functions F_8 to F_{13} and fixed dimension multimodal functions F_{14} to F_{23} by SSA method are reported in Tables 5 and 6, respectively. The results of SSA method have been compared with PSO, DE, GSA and GWO [22] methods and reported in Tables 5 and 6. Considering the results obtained for three types of test functions from F_1 to F_{23} , it is observed that all three heuristic methods have been able to find the global minimum with varying execution time. The interesting point of SSA might be its faster convergence except F_6 , F_{13} and F_{23} test functions. The minimum function value is found by SSA in almost all cases except F_6 , F_{13} and F_{21} functions. So, SSA is considered as a competitive new algorithm like GWO.

B. The economic emission of hybrid system

The inputs to the system are hourly load demand, hourly wind speed, cut-in, cut-out, rated speed of wind farm, rated power of wind farm, maximum and minimum pond level, maximum power that can be used in an hour by the unit for pumping or generating, pumping and generating efficiencies, cost and emission coefficients, maximum and minimum limits of

Table 1. Unimodal benchmark functions

Function	Dim	Range	$f_{\min}$
$f_1(x) = \sum_{i=1}^n x_i^2$	30	[-100,100]	0
$f_2(x) = \sum_{i=1}^n x_i + \prod_{i=1}^n x_i $	30	[-10,10]	0
$f_3(x) = \sum_{i=1}^n \left(\sum_{j=1}^i x_j \right)^2$	30	[-100,100]	0
$f_4(x) = \max_i \{ x_i , 1 \leq i \leq n\}$	30	[-100,100]	0
$f_5(x) = \sum_{i=1}^{n-1} [100(x_{i+1} - x_i^2)^2 + (x_i - 1)^2]$	30	[-30,30]	0
$f_6(x) = \sum_{i=1}^n ([x_i + 0.5])^2$	30	[-100,100]	0
$f_7(x) = \sum_{i=1}^n ix_i^4 + \text{rand}(0.1)$	30	[-1.28,1.28]	0

Table 2 Multimodal benchmark functions

Function	Dim	Range	$f_{\min}$
$f_8(x) = \sum_{i=1}^n -x_i \sin(\sqrt{ x_i })$	30	[-500,500]	-418.983×10^{-5}
$f_9(x) = \sum_{i=1}^n [x_i^2 - 10 \cos(2\pi x_i) + 10]$	30	[-5.12,5.12]	0
$f_{10}(x) = -20 \exp(-0.2 \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2}) - \exp\left(\frac{1}{n} \sum_{i=1}^n \cos(2\pi x_i)\right) + 20 + e$	30	[-32,32]	0
$f_{11}(x) = \frac{1}{4000} \sum_{i=1}^n x_i^2 - \prod_{i=1}^n \cos\left(\frac{x_i}{\sqrt{i}}\right) + 1$	30	[-600,600]	0
$f_{12}(x) = \frac{\pi}{n} \left\{ 10 \sin(\pi y_1) + \sum_{i=1}^{n-1} (y_i - 1)^2 [1 + 10 \sin^2(\pi y_{i+1})] + (y_n - 1)^2 \right\}$ $+ \sum_{i=1}^n u(x_i, 10, 100, 4)$ $y_i = 1 + \frac{x_i + 1}{4}$ $U(x_i, a, k, m) = \begin{cases} k(x_i - a)^m & x_i > a \\ 0 & -a < x_i < a \\ k(-x_i - a)^m & x_i < -a \end{cases}$	30	[-50,50]	0
$f_{13}(x) = 0.1 \{ \sin^2(3\pi x_1) + \sum_{i=1}^n (x_i - 1)^2 [1 + \sin^2(3\pi x_i + 1)] + (x_n - 1)^2 [1 + \sin^2(2\pi x_n)] \} + \sum_{i=1}^n u(x_i, 5, 100, 4)$	30	[-50,50]	0

thermal generation. The input data are provided in Table 7. The outputs obtained are the hourly wind power, hourly pumped storage power, and the hourly load dispatch schedule, generation cost & emission levels for one day for the three thermal units in three different objectives viz. most economical schedule, minimum emission schedule and best compromise EELD schedule.

The following two different cases have been considered.

- Case-1: A thermal power system with three conventional generators.
- Case-2: For the purpose of comparison, the hybrid system is considered with three conventional thermal generators, a wind generator and also a pumped storage plant.

B.1 Case 1: When only three thermal units used

- Economic dispatch (when J_1 is optimized)

Table 3. Fixed dimension multimodal benchmark functions

Function	Dim	Range	$f_{\min}$
$f_{14}(x) = \left(\frac{1}{500} + \sum_{j=1}^{25} \frac{1}{j - \sum_{i=1}^{25} (x_i - a_{ij})^6} \right)^{-1}$	2	[-65,65]	1
$f_{15}(x) = \sum_{i=1}^{11} \left[a_i - \frac{x_i(b_i^2 + b_i x_2)}{b_i^2 + b_i x_3 + x_4} \right]^2$	4	[-5,5]	0.00030
$f_{16}(x) = 4x_1^2 - 2.1x_1^4 + \frac{1}{3}x_1^6 + x_1x_2 - 4x_2^2 + 4x_2^4$	2	[-5,5]	-1.0316
$f_{17}(x) = \left(x_2 - \frac{5.1}{4\pi^2}x_1^2 + \frac{5}{\pi}x_1 - 6 \right)^2 + 10 \left(1 - \frac{1}{8\mu} \right) \cos x_1 + 10$	2	[-5,5]	0.398
$f_{18}(x) = [1 + (x_1 + x_2 + 1)^2(19 - 14x_1 + 3x_1^2 - 14x_2 + 6x_1x_2 + 3x_2^2)] \times [30 + (2x_1 - 3x_2)^2 \times (18 - 32x_1 + 12x_1^2 + 48x_2 * 36x_1x_2 + 27x_2^2)]$	2	[-2,2]	3
$f_{19}(x) = - \sum_{i=1}^4 c_i \exp \left(- \sum_{j=1}^3 a_{ij} (x_j - p_{ij})^2 \right)$	3	[1,3]	-3.86
$f_{20}(x) = - \sum_{i=1}^4 c_i \exp \left(- \sum_{j=1}^6 a_{ij} (x_j - p_{ij})^2 \right)$	6	[0,1]	-3.32
$f_{21}(x) = - \sum_{i=1}^5 [(X - a_i)(X - a_i)^T + c_i]^{-1}$	4	[0,10]	-10.1532
$f_{22}(x) = - \sum_{i=1}^7 [(X - a_i)(X - a_i)^T + c_i]^{-1}$	4	[0,10]	-10.4028
$f_{23}(x) = - \sum_{i=1}^{10} [(X - a_i)(X - a_i)^T + c_i]^{-1}$	4	[0,10]	-10.5363

Table 4. Results of unimodal benchmark functions

F	SSA		GWO [22]		GSA [22]		DE [22]		PSO [22]	
	Ave	Std	Ave	Std	Ave	Std	Ave	Std	Ave	Std
F ₁	2.618E-28	9.86E-06	6.59E-28	6.34E-05	2.53-E16	9.67E-17	8.2E-14	8.2E-14	0.000136	0.000202
F ₂	2.743E-17	0.01952	7.18E-17	0.029014	0.055655	0.194074	1.5E-09	9.9E-10	0.042144	0.045421
F ₃	4.98E-07	24.5318	3.29E-06	79.14958	896.5347	318.9559	6.8E-11	7.4E-11	70.12562	22.11924
F ₄	1.922E-07	1.21261	5.61E-07	1.315088	7.35487	1.741452	0	0	1.086481	0.317039
F ₅	26.1695	58.7627	26.81258	69.90499	67.54309	62.22534	0	0	96.71832	60.11559
F ₆	0.5009	0.00112	0.816579	0.012600	2.5E-16	1.7E-16	0	0	0.000102	8.28E-05
F ₇	0.0019	0.1139	0.002213	0.100286	0.083411	0.04339	0.00463	0.00120	0.122854	0.044957

In this case, the value of conversion factor (CF) = $x = 0.3632$ lb/\$ is used in equation (13) to get the total cost of economic emission solution. One can find the cost of operation, emission and combined cost & emission for the day were 36.74 k \$/Day, 27.48 k lb/Day and 54.9654 k \$/Day, respectively in Table 8.

Table 5 Results of multimodal benchmark functions

F	SSA		GWO [22]		GSA [22]		DE [22]		PSO [22]	
	Ave	Std	Ave	Std	Ave	Std	Ave	Std	Ave	Std
F ₈	-6350.1	-3876.68	-6123.1	-4087.44	-2821.07	493.0375	-11080.1	574.7	-4841.29	1152.814
F ₉	6.2416	28.0176	0.310521	47.35612	25.96841	7.470068	69.2	38.8	46.70423	11.62938
F ₁₀	1.18E-13	0.08025	1.06E-13	0.077835	0.062087	0.23628	9.7E-08	4.2E-08	0.276015	0.50901
F ₁₁	0.0122	0.01381	0.004485	0.006659	27.70154	5.040343	0	0	0.009215	0.007724
F ₁₂	0.0346	0.01269	0.053438	0.020734	1.799617	0.95114	7.9E-15	8E-15	0.006917	0.026301
F ₁₃	1.1886	1.0122	0.654464	0.004474	8.899084	7.126241	5.1E-14	4.8E-14	0.006675	0.008907

Table 6. Results of fixed dimension multimodal benchmark functions

F	SSA		GWO [22]		GSA [22]		DE [22]		PSO [22]	
	Ave	Std	Ave	Std	Ave	Std	Ave	Std	Ave	Std
F ₁₄	2.9821	3.0143	4.042493	4.252799	5.859838	3.831299	0.998004	3.3E-16	3.627168	2.560828
F ₁₅	0.000311	0.000617	0.000337	0.000625	0.003673	0.001647	4.5E-14	0.00033	0.000577	0.000222
F ₁₆	-1.0316	-1.0316	-1.03163	-1.03163	-1.03163	4.88E-16	-1.03163	3.1E-13	-1.03163	6.25E-16
F ₁₇	0.3979	0.3979	0.397889	0.397887	0.397887	0	0.397887	9.9E-09	0.397887	0
F ₁₈	3	3	3.000028	3	3	4.17E-15	3	2E-15	3	1.33E-15
F ₁₉	-3.8622	-3.8624	-3.86263	-3.86278	-3.86278	2.29E-15	NA	NA	-3.86278	2.58E-15
F ₂₀	-3.1973	-3.1429	-3.28654	-3.25056	-3.31778	0.023081	NA	NA	-3.26634	0.060516
F ₂₁	-10.153	-9.6213	-10.1514	-9.14015	-5.95512	3.737079	-10.1532	0.0000025	-6.8651	3.019644
F ₂₂	-10.4022	-9.2147	-10.4015	-8.58441	-9.68447	2.014088	-10.4029	3.9E-07	-8.45653	3.087094
F ₂₃	-10.5354	-9.2436	-10.5343	-8.55899	-10.5364	2.6E-15	-10.5364	1.9E-07	-9.95291	1.782786

- *Emission dispatch(when J_2 is optimized)*

It can also be found that the cost of operation, emission and combined cost & emission for the day were 45.0163 k \$/Day, 26.51 k lb/Day and 55.5066 k \$/Day, respectively in Table 9.

- *Economic emission dispatch(when J_3 is optimized)*

Further it can be seen that the cost of operation, emission and combined cost & emission for the day were 42.96 k \$/Day, 26.87 k lb/Day and 53.5909 k \$/Day, respectively from Table 10.

Table 7. Data of the three conventional thermal units

Details		GEN 1	GEN 2	GEN 3
Limits	Max Limit	200	150	125
	Min Limit	50	40	30
Cost Coefficients	a	105	44.1	40.6
	b	2.45	3.51	3.89
	c	0.01	0.01	0.01
	d	200	160	140
	e	0.035	0.038	0.04
Emission Coefficients	γ	0.0252	0.0275	0.0153
	β	-1.355	-1.249	0.8051
	α	22.983	137.37	368.704
	η	0.5035	0.5773	0.4966
	k	0.02075	0.02446	0.0227

Table 8 Best cost schedule using only thermal units

Time Hrs	Demand (MW)	PG_1	PG_2	PG_3	Cost (C)	Emission (E)	$C + x * E$
1	299	132.8238	103.4645	62.7116	1.4453	1.0867	2.1734
2	291	126.121	106.3652	58.5138	1.4063	1.0533	2.1067
3	305	136.5237	103.2125	65.2638	1.4759	1.1135	2.2269
4	301	134.3919	79.7266	86.8815	1.4567	1.0786	2.1571
5	306	131.8608	109.2735	64.8657	1.484	1.1153	2.2306
6	309	136.3588	71.661	100.9802	1.5074	1.1187	2.2373
7	311	140.5608	87.8824	82.5569	1.5067	1.1273	2.2547
8	317	140.4618	82.8537	93.6845	1.5431	1.1488	2.2975
9	320	139.5178	102.7846	77.6976	1.5553	1.1667	2.3335
10	321	138.5559	94.1166	88.3275	1.5618	1.16	2.32
11	329	139.4003	93.4097	96.1899	1.6074	1.1913	2.3826
12	322	140.6205	86.8256	94.5539	1.5693	1.167	2.334
13	317	141.2963	82.9576	92.7461	1.5423	1.1505	2.3011
14	314	139.0702	77.9754	96.9543	1.5295	1.1371	2.2742
15	313	141.5164	75.708	95.7756	1.5242	1.14	2.2801
16	322	143.543	104.9372	73.5198	1.5659	1.1875	2.375
17	319	137.8935	90.024	91.0825	1.552	1.15	2.3

18	320	134.9822	107.3069	77.7109	1.5571	1.162	2.3241
19	327	138.5356	100.7587	87.7057	1.5944	1.186	2.3719
20	333	142.0731	115.1726	75.7543	1.6288	1.237	2.4739
21	331	139.5265	96.8211	94.6524	1.6176	1.2003	2.4005
22	316	142.867	78.3925	94.7404	1.5387	1.1525	2.3049
23	309	139.7132	80.4852	88.8017	1.4988	1.1184	2.2368
24	303	138.265	112.4934	52.2416	1.4716	1.1343	2.2686
Total					36.74	27.48	54.9654

Table 9 Least emission schedule using only thermal units

Time in Hrs	Demand (MW)	PG_1	PG_2	PG_3	Cost	Emission	$C + x \cdot E$
1	299	104.425	92.248	102.327	1.8361	1.0387	2.2705
2	291	103.121	90.6404	97.2385	1.8248	1.0071	2.1362
3	305	105.746	94.8242	104.43	1.8467	1.063	2.2911
4	301	104.975	94.0181	102.007	1.8419	1.0467	2.1886
5	306	106.69	95.264	104.047	1.821	1.0671	2.2207
6	309	107.18	95.3651	106.455	1.8515	1.0796	2.3117
7	311	109.877	95.5743	105.549	1.8554	1.088	2.2309
8	317	109.139	98.2666	109.594	1.8736	1.1134	2.3157
9	320	111.271	98.6351	110.094	1.8824	1.1263	2.3475
10	321	111.779	99.97	109.252	1.8073	1.1307	2.265
11	329	113.585	99.5795	115.835	1.9525	1.1659	2.4605
12	322	111.345	99.2279	111.427	1.8991	1.135	2.3522
13	317	109.768	97.6021	109.63	1.8736	1.1133	2.3361
14	314	109.958	95.8984	108.144	1.8573	1.1006	2.2803
15	313	109.497	95.7628	107.74	1.8563	1.0964	2.3204
16	322	110.834	98.8689	112.297	1.9082	1.135	2.3796
17	319	109.635	98.4658	110.9	1.8899	1.122	2.3613
18	320	110.839	99.1801	109.981	1.8817	1.1263	2.324

19	327	111.495	99.5896	115.915	1.952	1.1571	2.3911
20	333	113.874	101.981	117.145	1.9711	1.1839	2.4472
21	331	114.447	101.41	115.144	1.9475	1.1748	2.4234
22	316	108.511	98.0627	109.426	1.8705	1.1091	2.3399
23	309	105.84	96.2721	106.888	1.8513	1.0797	2.3057
24	303	105.286	94.6225	103.091	1.8646	1.0549	2.207
Total					45.0163	26.51	55.5066

B.2 Case 2: The hybrid system

The input data of the wind generator and the pumped storage plant are provided in Table 11. It is considered that negative pumped storage power indicates the unit is operating in pumping mode thus it is consuming power from the system and positive pumped storage power indicates the unit is operating in generating mode thus it is delivering power to the system. A tabular analysis of power output from wind and pumped storage plant is provided in Table 12. After getting almost constant output from the component 1 and 2, which is the wind and the pumped storage units, the rest part of the load demand is to be scheduled and met by the three conventional thermal units. The power output of pump storage plant, wind generator and the hybrid system are depicted in Figure. 4. The reduced load demands is shared between the three thermal units and are again scheduled in three different sub cases as given below.

Table 10 Best compromised solution using only thermal units

Time in Hrs	Demand (MW)	PG_1	PG_2	PG_3	Cost	Emission	$C + x \cdot E$
1	299	97.7279	101.9528	99.3193	1.7034	1.0423	2.0865
2	291	121.1898	71.0874	98.7228	1.5815	1.0279	2.0477
3	305	121.9987	76.63	106.3713	1.7781	1.079	2.1655
4	301	121.697	76.4206	102.8824	1.8251	1.0625	2.1254
5	306	125.6817	79.0225	101.2958	1.7409	1.0842	2.1527
6	309	127.2174	71.7301	110.0525	1.7586	1.1068	2.1934
7	311	123.5207	80.288	107.1913	1.7981	1.1016	2.2005
8	317	128.1366	80.6323	108.2311	1.7948	1.1308	2.255
9	320	124.9872	92.4125	102.6004	1.8441	1.1338	2.2721
10	321	113.1755	96.8993	110.9252	1.8015	1.1308	2.2616
11	329	128.0132	96.4045	104.5824	1.855	1.1739	2.3478
12	322	129.3874	84.0569	108.5557	1.8102	1.1504	2.2933

13	317	134.3674	78.07	104.5626	1.769	1.1409	2.2562
14	314	123.0089	89.1815	101.8096	1.8355	1.1082	2.2283
15	313	102.1325	105.843	105.0246	1.8553	1.1	2.2255
16	322	135.4707	90.0369	96.4924	1.8168	1.1566	2.2948
17	319	135.1209	77.5366	106.3425	1.7653	1.1509	2.276
18	320	134.6747	105.5439	79.7814	1.817	1.1587	2.2869
19	327	125.1167	93.3821	108.5013	1.8494	1.1629	2.3322
20	333	118.9373	104.6382	109.4246	1.9092	1.1854	2.3709
21	331	127.7424	100.39	102.8676	1.858	1.1827	2.3594
22	316	117.0421	91.7284	107.2294	1.7204	1.1116	2.2231
23	309	138.0961	71.9083	98.9956	1.7196	1.1214	2.2033
24	303	94.942	113.7655	94.2925	1.7568	1.0705	2.1328
Total					42.96	26.87	53.5909

- Economic dispatch(when J_1 is optimized):

One can find the cost of operation, emission level and combined cost & emission for the day are 32.8359 k \$/Day, 24.6756 k lb/Day and 49.3515 k \$/Day, respectively in Table 13.

Table 11. Data of the wind plant and pumped storage power plant

Parameter	V_{ci}	V_{co}	V_r	P_r	$PP_{\max} = PG_{\max}$	η_g	η_p
Value	5 m/s	30 m/s	15 m/s	50 MW	40 MW	0.8447	0.871

- Emission dispatch(when J_2 is optimized)

It can also be found that the cost of operation, emission level and combined cost & emission for the day are 43.0697 k \$/Day, 23.5423 k lb/Day and 50.5092 k \$/Day, respectively in Table 14.

- Economic emission dispatch (when J_3 is optimized)

Further, it can be seen that the cost of operation, emission level and combined cost & emission for the day are 38.8556 k \$/Day, 23.8526 k lb/Day and 47.519 k\$/Day, respectively in Table 15. The convergence nature of the proposed algorithm is shown in Table 16. The search space is squeezed between two boundaries and converged to a single value. The curve in Figure. 5 shows the reduction of search space algorithm for all the three thermal generators. A graph is plotted between the difference of the maximum cost and minimum cost in each reduced search space in other words the convergence is shown in Figure. 6.

Table 12 Evaluation of power output for wind farm & pumped storage units

Time in hrs	Wind speed in m/s	Wind power (MW)	Pond level (MW)	Pumped storage power (MW)	PW+PS (MW)	Demand (MW)	PD for thermal (MW)
1	35	42.8571	11.1986	-11.1986	31.6586	299	267.3414
2	34	41.4286	21.1529	-9.9543	31.4743	291	259.5257
3	36	44.2857	33.5957	-12.4429	31.8429	305	273.1571
4	33	40	42.3057	-8.71	31.29	301	269.71
5	26	30	42.3057	0	30	306	276
6	36	44.2857	54.7486	-12.4429	31.8429	309	277.1571
7	36	44.2857	67.1914	-12.4429	31.8429	311	279.1571
8	36	44.2857	79.6343	-12.4429	31.8429	317	285.1571
9	35	42.8571	90.8329	-11.1986	31.6586	320	288.3414
10	36	44.2857	100	-9.1671	35.1186	321	285.8814
11	22	24.2857	93.2351	6.7649	31.0506	329	297.9494
12	19	20	81.3966	11.8385	31.8385	322	290.1615
13	17	17.1429	66.1756	15.221	32.3638	317	284.6362
14	12	10	42.4986	23.677	33.677	314	280.323
15	12	10	18.8216	23.677	33.677	313	279.323
16	19	20	6.983	11.8385	31.8385	322	290.1615
17	28	32.8571	9.4716	-2.4886	30.3686	319	288.6314
18	34	41.4286	19.4259	-9.9543	31.4743	320	288.5257
19	36	44.2857	31.8688	-12.4429	31.8429	327	295.1571
20	12	10	8.1917	23.677	33.677	333	299.323
21	15	14.2857	0	8.1917	22.4774	331	308.5226
22	19	20	0	0	20	316	296
23	28	32.8571	2.4886	-2.4886	30.3686	309	278.6314
24	22	24.2857	0	2.4886	26.7743	303	276.2257

The best cost solution, least emission solution and best compromising solution for both the systems; those are with the three conventional thermal units only and for the hybrid system are summarized in the Table 17. In hybrid system, the net saving of cost and emission level are found to be 4.1044 k \$/Day and 3.0174 k lb/Day, respectively in comparison to power system having only thermal generators.

From Figures 4-6 and Table 17, it is very clear that space search algorithm having good convergence characteristics and yields better results in a hybrid system.

Table 13. Best cost schedule for three thermal units in the hybrid system

Time	Thermal Demand	GEN 1	GEN 2	GEN 3	Cost	Emc	C+x*E
1	267.3414	141.0819	65.0119	61.2476	1.2806	0.9954	1.9909
2	259.5257	124.6683	76.8503	58.0072	1.2387	0.9287	1.8575
3	273.1571	138.5146	79.6883	54.9543	1.3081	1.0051	2.0102
4	269.71	134.8567	70.8858	63.9674	1.2908	0.982	1.9641
5	276	119.2089	97.2987	59.4924	1.3269	0.9806	1.9613
6	277.1571	127.8813	67.1335	82.1423	1.3343	0.9907	1.9814
7	279.1571	126.1643	74.0475	78.9454	1.3422	0.9898	1.9797
8	285.1571	135.3343	64.893	84.9298	1.3769	1.0353	2.0706
9	288.3414	139.9532	65.7299	82.6584	1.3922	1.0561	2.1122
10	285.8814	137.169	87.9301	60.7824	1.3733	1.0412	2.0824
11	297.9494	139.4742	74.1452	84.33	1.4403	1.0816	2.1631
12	290.1615	134.8157	67.9964	87.3494	1.4027	1.0486	2.0972
13	284.6362	136.2946	72.6609	75.6807	1.3689	1.0302	2.0604
14	280.323	124.892	84.2865	71.1444	1.3459	0.9915	1.9829
15	279.323	132.0817	97.8384	49.4029	1.3435	1.0235	2.047
16	290.1615	130.8992	72.4189	86.8433	1.4016	1.0371	2.0743
17	288.6314	131.153	105.5377	51.9408	1.3939	1.0593	2.1186
18	288.5257	129.5307	69.8658	89.1293	1.395	1.031	2.0619
19	295.1571	135.8325	72.9305	86.3941	1.4269	1.0643	2.1286
20	299.323	129.7475	75.9904	93.585	1.452	1.066	2.132
21	308.5226	139.5278	78.6823	90.3125	1.4972	1.117	2.234
22	296	137.0593	107.9091	51.0315	1.4331	1.1014	2.2028
23	278.6314	129.2533	71.6595	77.7186	1.339	0.9952	1.9904
24	276.2257	139.59	57.5155	79.1203	1.3319	1.024	2.048
Total					32.8359	24.6756	49.3515

Table 14 Least emission schedule for three thermal units in the hybrid system

Time	Thermal Demand	GEN 1	GEN 2	GEN 3	Cost	Emc	C+x*E
1	267.3414	95.5374	85.0861	86.718	1.7864	0.9191	2.0347
2	259.5257	91.8277	82.7786	84.9193	1.7569	0.892	2.0138
3	273.1571	98.2335	86.321	88.6027	1.8057	0.94	1.9991
4	269.71	96.4623	85.7797	87.4681	1.6297	0.9276	1.9305
5	276	97.9284	87.4965	90.5751	1.7902	0.9503	2.0578
6	277.1571	99.1554	87.2867	90.715	1.794	0.9546	2.085
7	279.1571	98.3225	88.7395	92.0952	1.8182	0.962	2.0653
8	285.1571	100.57	89.8299	94.7572	1.8435	0.9846	2.1075
9	288.3414	101.9155	90.1432	96.2828	1.7244	0.9968	2.0636
10	285.8814	100.7006	89.6114	95.5695	1.7282	0.9873	2.0698
11	297.9494	104.4928	92.9644	100.4921	1.8372	1.0345	2.2416
12	290.1615	102.3672	91.3438	96.4505	1.8409	1.0038	2.1436
13	284.6362	99.9814	89.415	95.2398	1.81	0.9826	2.1751
14	280.323	99.2783	88.6683	92.3763	1.8018	0.9663	2.0984
15	279.323	99.074	87.8119	92.437	1.798	0.9626	2.0918
16	290.1615	102.813	90.6295	96.719	1.7644	1.0038	2.1137
17	288.6314	101.4196	90.9125	96.2993	1.8671	0.9979	2.1012
18	288.5257	101.3939	90.7183	96.4135	1.7736	0.9975	2.0538
19	295.1571	103.4257	92.1956	99.5358	1.832	1.0234	2.2681
20	299.323	104.7031	93.3515	101.2683	1.7944	1.04	2.1673
21	308.5226	107.493	95.2723	105.7572	1.8515	1.0776	2.3072
22	296	104.9212	92.0056	99.0731	1.8345	1.0267	2.2508
23	278.6314	99.039	87.4876	92.1048	1.7963	0.9601	2.032
24	276.2257	97.5576	87.9627	90.7054	1.7908	0.9512	2.0375
Total					43.0697	23.5423	50.5092

Figure.4 Load shared by each component of the hybrid system

Table 15. Best compromised solution schedule for the 3 thermal units in the hybrid system

Time	Thermal Demand	GEN 1	GEN 2	GEN 3	Cost	Emc	$C + x \cdot E$
1	267.3414	73.5836	94.7282	99.0296	1.6208	0.9369	1.8602
2	259.5257	107.801	62.0217	89.7031	1.3848	0.9106	1.8093
3	273.1571	81.2281	96.2231	95.7059	1.68	0.95	1.9009
4	269.71	85.8231	100.3053	83.5816	1.52	0.937	1.8666
5	276	95.4103	93.6516	86.9382	1.6528	0.952	1.9106
6	277.1571	116.6405	63.8367	96.6798	1.6835	0.9799	1.936
7	279.1571	83.7703	107.3014	88.0854	1.5652	0.9791	1.9412
8	285.1571	92.5365	107.8185	84.8021	1.4263	0.9977	1.9954
9	288.3414	85.4751	110.0752	92.7911	1.6124	1.0151	2.0124
10	285.8814	119.2834	76.7858	89.8123	1.7456	1.0015	1.9897
11	297.9494	116.5825	77.1928	104.1741	1.5961	1.0457	2.0904
12	290.1615	85.4112	110.0788	94.6714	1.6281	1.022	2.026
13	284.6362	111.3925	78.6867	94.557	1.555	0.989	1.9754
14	280.323	88.453	101.6027	90.2673	1.7369	0.9746	1.9458
15	279.323	114.106	73.3999	91.8171	1.4974	0.9748	1.9456
16	290.1615	119.4441	73.6663	97.0511	1.6738	1.0202	2.0248
17	288.6314	102.0909	94.1927	92.3479	1.6004	0.9986	1.9965
18	288.5257	101.0572	97.0948	90.3737	1.5081	0.9994	1.9987
19	295.1571	110.9231	71.2592	112.9749	1.7287	1.0405	2.0718
20	299.323	98.9213	104.8682	95.5335	1.6355	1.0454	2.0874
21	308.5226	129.3367	72.4571	106.7287	1.7422	1.1058	2.1839
22	296	84.6236	111.6186	99.7577	1.7309	1.0472	2.0791
23	278.6314	110.3047	99.0054	69.3213	1.5983	0.9753	1.9452
24	276.2257	90.0101	86.3412	99.8744	1.7328	0.9543	1.9261
Total					38.8556	23.8526	47.519

Figure 5. Reduction of space to be searched in each iteration

Table 16. Convergence of space search between two boundaries within 15 iterations for the three thermal generators

$PG_{\max}$ (MW)			DIFF	$PG_{\min}$ (MW)		
GEN 1	GEN 2	GEN 3		GEN 1	GEN 2	GEN 3
200	150	125		50	40	30
142.4583	122.8714	109.876	341.5951	50.0612	40.7565	31.5893
141.5843	120.3753	91.6122	337.684	120.8539	43.0293	30.8242
135.9113	119.4343	49.4843	301.8613	121.7976	104.9438	31.0589
123.0747	111.1722	48.2051	44.1508	122.4031	105.359	42.6504
122.8861	106.7677	47.7999	12.7034	122.5237	105.5808	46.7493
122.7713	106.1321	47.7316	2.8002	122.6162	105.7395	47.4087
122.7653	105.9536	47.7101	1.2807	122.6962	105.7794	47.566
122.7523	105.8506	47.6861	0.8241	122.7052	105.8058	47.656
122.7332	105.8306	47.6828	0.3924	122.7123	105.8117	47.6745
122.7327	105.8246	47.6823	0.1477	122.7239	105.8128	47.6772
122.7326	105.8199	47.6811	0.102	122.7258	105.814	47.6791
122.7302	105.8187	47.681	0.065	122.7266	105.815	47.68
122.7292	105.8175	47.6808	0.0337	122.7276	105.8158	47.6805
122.7289	105.8167	47.6808	0.0178	122.7283	105.8161	47.6807
122.7289	105.8167	47.6808	0.0067	122.7283	105.8161	47.6807

Figure 6. Convergence obtained by using the proposed algorithm

Table 17. The best cost, minimum emission level and compromised cost of operation are compared between two system

Cases		Cost (k \$/Day)	Emission (k lb/Day)	Cost+ Emission (k\$/Day)
Thermal System	best cost	36.74	27.48	54.9654
	least emission	45.0163	26.51	55.5066
	compromised	42.96	26.87	53.5909
Hybrid System	best cost	32.8359	24.6756	49.3515
	minimum emission	43.0697	23.5423	50.5092
	compromised	38.8556	23.8526	47.519

6. Conclusion

This paper described an efficient algorithm as space search algorithm based on fuzzy coordination method which has been applied to a hybrid system. Initially, twenty three test functions were employed in order to benchmark the performance of the proposed algorithm. The results confirmed that SSA was able to provide highly competitive results compared to other established heuristic methods such as DE, PSO, GSA and GWO. Moreover, the results obtained by SSA with challenging search spaces provide superior performance. The proposed method is applied to a real hybrid system comprising of pump storage plant, wind generator and thermal generators to solve EELD problem with equality and inequality constraints. The original two objectives are transformed into a single objective optimization problem by using fuzzy logic by maximizing the membership function. The optimization computation is conducted on two test power systems. The hybrid system yields better efficient economic dispatch results than the conventional power system. Security and reliability analysis along with probabilistic wind model may be adopted using the proposed algorithm.

7. References

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LIST OF NOTATIONS USED

Dim : Dimension of benchmark function

f_{min} =Optimum function value

$P_w(t)$ = the wind power output in MW at time t .

$V(t)$ = the wind speed in m/s at time t .

V_{ci} = the cut in speed.

V_{co} = the cut out speed.

V_r = 15 m/sec, is the rated wind speed.

P_r = 50 MW, is the rated output power of the wind farm.

PL_t = Pond level expressed in terms of MW at time t .

M = 1 hr, is the time interval.

PG_t = power generated by pumped storage unit at time t in MW.

PP_t = power used for pumping by the unit at time t in MW.

$PP_{max} = PG_{max}$, the max power that can be used for pumping or generating by the unit in an hour

η_g = the generating efficiency of the pumped storage unit

η_p = pumping efficiency of the pumped storage unit J_1 = objective function for least cost.

J_2 = objective function for least emission

J_3 = objective function for best compromising solution

$CF = Min(Emc) / Min(Cost)$ in a sample space, is the conversion factor

Emc =operating emission that is specified by equation.

OC = operating cost that is specified by equation.

P_i = output of the i^{th} generator

n = the number of thermal generators

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