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Multi-Objective Optimal Dispatch Solution of Solar-Wind-Thermal System Using Improved Stochastic Fractal Search Algorithm

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***Abstract*—**This paper presents solution of multi-objective optimal dispatch (MOOD) problem of solar-wind-thermal system by improved stochastic fractal search (ISFSA) algorithm. Stochastic fractal search (SFSA) is inspired by the phenomenon of natural growth called fractal. It utilizes the concept of creating fractals for conducting a search through the problem domain with the help of two main operations diffusion and updating. To improve the exploration and exploitation capability of SFSA, scale factor is used in place of random operator. The SFSA and proposed ISFSA is implemented and tested on six different multi objective complex test systems of power system. TOPSIS is used here as a decision making tool to find the best compromise solution between the two conflicting objectives. The outcomes of simulation results are also compared with recent reported methods to confirm the superiority and validation of proposed approach.

Index Terms—Meta-heuristic, MOOD, TOPSIS, Fractals, Renewable energy.

I. INTRODUCTION

Economic load dispatch (ELD) is an important issue related to power system operation and control with goal is to reduce the total operating cost of electricity generation while satisfying all complex practical operating constraints. With the increase of environment awareness, pollution contributed by the thermal power plants, the ELD cannot fulfill the sustainability of the environment because of high amount of emitted pollutants. A possible solution of this problem is to switch to the low emission fuels but this is economical in long term due to its high price and low availability. On the other hand, economic emission dispatch (EED) recently becoming more popular. In EED both cost and emission minimized together for the optimal operation of the thermal power plant and sustainability of the environment without switching to low emission fuels.

EED is a complicated multi-objective constrained optimization problem with two competing objectives as cost and emission. These problems are solved by converting the problem as single objective problem using weighted sum approach. Different weights are assigned to fuel cost and emission to get an optimal Pareto front, which helps to find out the best compromise solution (BCS).

Earlier EED was solved by goal programming method [1] or weighted min-max method [2]. But in the last decade various nature inspired algorithm were developed to solve the EED problem like Differential Evolution (DE) [3], simulated annealing (SA) algorithm [4], Bacterial foraging algorithm (BFA) [5]- [6] Teaching learning based optimization (TLBO) [7], gravitational search algorithm(GSA) [8], Real coded Chemical Reaction algorithm(RCCRO) [9], Backtracking search algorithm (BSA) [10] and etc. Also algorithm likeCuckoo Search Algorithm (CSA) [25],Cat Swarm Optimization (CSO)[26] and Ant Colony Optimization(ACO) [27] are used for optimization of real world problem.

Demand of electricity is increasing day by day and hence utilization of renewable energy resources such as wind and solar power has been increasing over the past decade to reduce the energy crisis as well as to reduce environmental pollution especially global warming. However large scale integration of wind and solar power into existing power grid creates new operational challenges in the resulting ELD problem. The main problem associated with photo-voltaic (PV) system is weather controlled power generation and very high initial capital cost as compared to the same size of a diesel generator but the operating cost is very low and also the pollution is zero for the PV system. On the other hand, unpredictable nature of wind power creates more complication in ELD model. Hence reformulation of classical ELD model [11] is required considering issues as probabilistic based modeling of wind power, Impact of solar and wind power on emission emitted by thermal power plant. Also complex model of combined solar-wind-thermal system requires efficient algorithm. The wind integrated ED modeling can be presented in [12-14]. Modeling of hybrid solar-wind system is presented in [15] whereas modeling of integrated solar-wind-thermal system is presented in [16]. A comprehensive review of hybrid renewable energy system by evolutionary algorithms is presented in [17].

In this paper a novel optimization algorithm namely Improved Stochastic Fractal Search Algorithm (ISFSA) is used to solve the MOOD problems with and withoutrenewable power integration. ISFSA utilizes scale factor in place of random operator in Stochastic Fractal Search Algorithm (SFSA) [18] to enhance exploration and exploitation capability during optimization.

This paper is organized as: Problem formulation for MOOD problem, modeling of PV system and modeling of wind farm are presented in section 2. The idea behind SFSA and its improvisation is presented in section 3 and section 4. TOPSIS for selection of best compromise solution is presented in section 5. The implementation process of ISFSA for solution of MOOD problem are depicted in section 6, whereas section 7 presents result and discussion of simulation results. Finally concluding remarks is presented in section 8.

II. Multi Objective Optimal Dispatch

The objective for a solar-wind-thermal system is the simultaneous minimization of total operating cost and emitted emission.

A. Minimization of Cost:

As the solar power plant has no operating cost, Total operating cost (F_t) consist thermal cost and the cost associated with wind power depicted as:

$$min \quad F_t = \sum_{i=1}^{m} F_{th}(P_i) + \sum_{j=1}^{n} F_w(P_{wind}^j) \tag{1}$$

$F_{th}(P_i)$ is thermal cost and $F_w(P_{wind}^j)$ is the cost associated with wind power generation. The cost associated with thermal power generation can be represented as:

$$F_{th}(P_i) = (a_i P_i^2 + b_i P_i + c_i)(\$/\text{hr.}) \tag{2}$$

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

Considering valve point loading (VPL) effect thermal power generation cost depicted as:

$$F_{th}(P_i) = a_i P_i^2 + b_i P_i + c_i + \left|d_i sin\left(e_i\left(P_i^{min} - P_i\right)\right)\right|(\$/\text{hr.}) \tag{3}$$

Where, $d_i$and $e_i$are fuel cost coefficients corresponding to VPL effect; m is the number of thermal units.

The cost associated with wind power output using wind power coefficient K_j as given hereunder [12]

$$F_w\left(P_{wind}^j\right) = \sum_{j=1}^{n} K_j \times P_{wind}^j \tag{4}$$

n is the number of wind farm.

B. Minimization of Emission:

Here objective is to minimize emission depicted as:

$$min\ E_t = \sum_{i=1}^{m} E_{th}(P_i) \tag{5}$$

$$E_{th}(P_i) = (\alpha_i P_i^2 + \beta_i P_i + \gamma_i) \tag{6}$$

$$E_{th}(P_i) = (\alpha_i P_i^2 + \beta_i P_i + \gamma_i) + \zeta_i \exp(\lambda_i P_i) \tag{7}$$

E_{th} is the total amount of emission in ton/hr, andα_i, β_i , λ_i , ζ_i, λ_i are the emission coefficients of i^{th} generator.

C. Problem formulation of MOOD

Here bi-objective problem is converted into a single objective one using weighted sum approach as [22]:

$$F_{TOTAL} = w \times F_t + (1 - w) \times E_t;\ w \in (0,1) \tag{8}$$

Subjected to following constraints

D. Equality constraints

$$P_D + P_L = \sum_{i=1}^{m} P_i + P_{PV} + \sum_{j=1}^{n} P_{wind}^j \tag{9}$$

P_D represents the system power demand (MW), P_L is the total transmission loss of the system (MW). P_L is obtained using B-matrix coefficient as [11]:

$$P_L = \sum_{i=1}^{m} \sum_{j=1}^{m} P_i B_{ij} P_j + \sum_{i=1}^{m} B_{oi} P_i + B_{oo} \tag{10}$$

E. Inequality constraints

Generation power should lie within minimum and maximum values.

$$P_i^{min} \le P_i \le P_i^{max} \tag{11}$$

P_i^{min} and P_i^{max} is the minimum and maximum generation capacity for i^{th} thermal units.

II -A. Modeling of Photo-Voltaic System

Power output of photo-voltaic (PV) system is represented as [20]:

$$P_{PV} = \eta A \lambda \tag{12}$$

Where P_{PV} is the power output in MW/h, A is the total area of the photo-voltaic cell in m^2, $\boldsymbol{\lambda}$ (KWh/m^2) is the total radiation incident on PV system and η is the system efficiency.

$$\eta = \eta_1 \eta_2 P_f \tag{13}$$

Where, η_1 is the module efficiency, η_2 is the power conditioning efficiency and P_f is the packing factor.

$$\eta_1 = \eta_r[1 - \beta\left(T_c - T_{ref}\right)] \tag{14}$$

Where, η_r is the module reference efficiency, β is array efficiency temperature coefficient, $T_c$is the monthly average cell temperature and T_{ref} is the reference temperature. The radiation and temperature data are adopted from [21], and also presented in Appendix A.

II-B. Modeling of Wind Farm

Exact wind speed and power forecast majorly affects wind farm ideal dispatch. The wind velocity is an arbitrary variable and wind power imparts a nonlinear connection to it. The wind speed information from different places is found to take after Weibull distribution nearly and it is use for processing wind speed and wind power**.**

Probability density function of wind velocity is expressed as [12]:

$$pdf(u) = \frac{\beta}{\alpha}\left(\frac{u}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{u}{\alpha}\right)^{\beta}\right] \quad (15)$$

Hera α and β are shape and scale factor respectively. The wind power (W_p) can be represented as a stochastic variable and calculated from wind speed as [12].

$$P_{wind}^{j} = \begin{cases} 0 & (u < u_{ci} \ or\ u \geq u_{co}) \\ P_{wind}^{jR} & (u_r \leq u < u_{co}) \\ \frac{(u-u_{in})P_{wind}^{jR}}{u_r - u_{in}} & (u_{ci} \leq u < u_r) \end{cases} \quad (16)$$

Here u_r, u_{ci} and u_{co} are rated wind speed, cut-in speed and cut-out speed respectively. P_{wind}^{j} is the wind power output of j[th] wind unit. It is quite clear from (16) that when wind speed is either less than the cut-in speed or greater than the cut-out speed the wind power output is zero. The power output of the wind unit is a continuous variable when the wind speed is between the rated and cut-in speed and the pdf is given as per the (15) The total of all wind generator yields is taken as one random variable P_{wind}^{j} and the pdf is given by

$$pdf(P_{wind}) = \frac{\beta\gamma u_{in}}{P_{wind}^{jR}\alpha}\left[\frac{\left(1+\frac{\gamma P_{wind}^{j}}{P_{wind}^{jR}}\right)u_{in}}{\alpha}\right]^{\beta-1} .exp\left[-\left\{\frac{(1+\frac{\gamma P_{wind}^{j}}{P_{wind}^{jR}})v_{in}}{\alpha}\right\}^{\beta}\right] \quad (17)$$

Here $\gamma = \left(\left(\frac{u_r}{u_{ci}}\right) - 1\right)$.

To describe the condition that the available power is not ample to satisfy the total demand with losses, a probabilistic tolerance δ_a is chosen to model the uncertainty of wind power availability. In context to this the power balance constraint in (9) with wind and solar power is modified as expressed below.

$$P_r(\sum_{j=1}^{n} P_{wind}^{j} + \sum_{i=1}^{m} P_i \ + P_{PV} \leq (P_D + PLoss) \leq \delta_a \quad (18)$$

A smaller value of δ_a decreases the risk of not enough wind power and increases the thermal generation to ensure the good reserve capacity.

III. Stocastic Fractal Search Algorithm (SFSA)

Stochastic fractal search is a bio inspired algorithm developed by Hamid Salimi in 2015 [18]. It is a meta-heuristic type algorithm which imitates the phenomenon of natural growth. It used the mathematical tool of fractal to imitate the growth. A fractal is a repeated graphical pattern which can be observed on many natural objects like leaves of trees, wings of peacock or patterns created in the sky due to electrical discharge. The SFSA utilizes the concept of creating fractals for conducting a search through the problem domain. The random fractals are generated by using any mathematical method like Levy flight, Gaussian walks, percolation clusters or Brownian motion. The main operations performed are diffusion and updating.

In SFSA diffusion is carried out using Gaussian distribution. Each solution diffuses around its current position and generates similar solutions until a cluster is formed, promoting exploitation by each point around its current position. Updating is done in two steps to change the position of each solution. The first step mutates the elements of solution points and in the second step the whole solution is changed. Updating process is carried out on the basis of a probability assigned to each solution such that better solutions have lesser probability of change and higher chances of being retained unaltered.

IV. Improved Stocastic Fractal Search Algorithm (ISFSA)

The initial solutions are generated according to the equation depicted below within specified upper limit (UB) and lower limit (LB)

$$r_i = LB + F \ * (UB - LB) \quad (19)$$

where F is the user defined parameter.

Stochastic Fractal Search has two important processes called diffusion and updating which are discussed as below.

A. Diffusion Process

Here points are generated in the search space to enhance exploitation capability of an algorithm that increases the probability of finding local minima.

To generate different points Gaussian walks is utilized as per the (20) and (21).

$$GW_1 = gaussian(\mu_{BP}, \sigma) + \varepsilon \times BP - \varepsilon' \times r_i \quad (20)$$

$$GW_2 = gaussian(\mu_q, \sigma) \quad (21)$$

Where ε and έ are uniformly distributed random numbers between 0 and 1, r_i and BP arei^{th}point and best point in the group respectively. $\mu_{BP} = |BP|$ and $\mu_q = |r_i|$.

σ is the standard deviation represented as below.

$$\sigma = \frac{\log(g)}{g} \times (r_i - BP) \quad (22)$$

The factor $\frac{\log(g)}{g}$ decreases the size of the Gaussian jumps as iteration(g) growths during simulation.

B. Updating Process

After initialization as in (19) all points in the search space, their fitness is evaluated and the best point (BP) is identified, then this point is diffused around the initial position and different points are generated by (20) or Eq. (21).

Then ranking process is carried out for all points based on their fitness. On the basis of fitness of points probabilities are assigned to all these points uniformly to these points according to the (23).

$$r_{ai} = \frac{rank(r_i)}{N} \quad (23)$$

Where, $rank(r_i)$ is the r ank of point r_i among the other points in the group and N is the number of points in the group.

For each point r_i in group based on either condition $r_{ai} < \varepsilon$ is satisfied or not, the j_{th} component of r_i is updated according to the equation below otherwise it remains unchanged.

$$r_i' = r_r\,(j)\text{-}\epsilon \times \left(r_t(j) - r_i(j)\right) \quad (24)$$

r_i' is the new modified position of r_i , r_r and r_t are random selected points.

In second updating phase, the positions of all points are modified with respect to the position of other points in the group. It helps to improve the quality of exploration.

All points obtained from the first updating process are ranked again according to the (23) If $r_{ai} < \varepsilon$ for the i^{th} position is held for a new point r_i' , the current position of r_i' is modified according to the (25) and (26) as depicted below otherwise remains unchanged.

$$r_i'' = r_i' + \varepsilon' \times (r_t' - BP) \quad if \quad \varepsilon' \leq 0.5 \quad (25)$$

$$r_i'' = r_i' + \varepsilon' \times (r_t' - (r_r') \quad if \quad \varepsilon' > 0.5 \quad (26)$$

Where r_t' *and* r_r' are random selected points obtained from the first updating process, ε' is random number generated by the Gaussian distribution. If the fitness of new solution is found to be better, then only r_i'' is replaced by r_i'.

V. TOPSIS

TOPSIS stands for technique for order preference by similarity to an ideal solution (TOPSIS) [23]. TOPSIS is a tool to find the best compromise solution between the conflicting objectives. TOPSIS tries to find the solution which is nearer to the ideal solution. Working of TOPSIS is summed up here-under in steps [24].

Step-1 In step-1 the normalized decision matrix is obtained as mentioned below:

$$a_{ij} = \frac{b_{ij}}{\sqrt{sum(b_{ij}^2)}} \quad for\ i = 1,2,---k;\ j = 1,2,--l \quad (27)$$

Where, a_{ij} and b_{ij} are normalized and original decision matrix and k is the number of alternative solution and l is the number of alternatives.

Step-2 In step-2 normalized weighted matrix is calculated from the normalized decision matrix as mentioned in step-1, which is calculated from (28)

$$\Theta_{ij} = W_j \times a_{ij} \quad (28)$$

W_j is a matrix in which weights are assigned to the objectives and Θ_{ij} is the weighted normalized decision matrix.

Step-3 In step-3 positive and negative ideal solution are identified as per(29) and (30) respectively.

$$P^* = [\Theta_1^*, \Theta_2^*, ---\Theta_n^*]$$

and

$$\Theta_j^* = \left\{\max\left(\Theta_{ij}\right) \quad if\ j \in J;\ \min\left(\Theta_{ij}\right)\ if \quad j \in J'\right\} \quad (29)$$

$$P' = [\Theta_1', \Theta_2', ---\Theta_n']$$

and

$$\Theta_j' = \left\{\min(\Theta_{ij}) \quad if\ j \in J;\ \max\left(\Theta_{ij}\right)\ if \quad j \in J'\right\} \quad (30)$$

Step-4 In step-4 geometric distances from the positive and negative ideal solutions are calculated as per the (31) and (32)

$$\mu_i^* = \sqrt{\textstyle\sum_{j=1}^{l}(\Theta_{ij} - \Theta_j^*)^2)} \quad (31)$$

$$\mu_i' = \sqrt{\textstyle\sum_{j=1}^{l}(\Theta_{ij} - \Theta_j')^2} \quad (32)$$

Step-5 In this step TOPSIS rank is calculated with respect to the closeness of ideal solution as:

$$\mu_i = \frac{\mu_i'}{\mu_i^* + \mu_i'} \quad (33)$$

Higher values of TOPSIS rank indicates that the equivalent solution is close to the ideal solution.

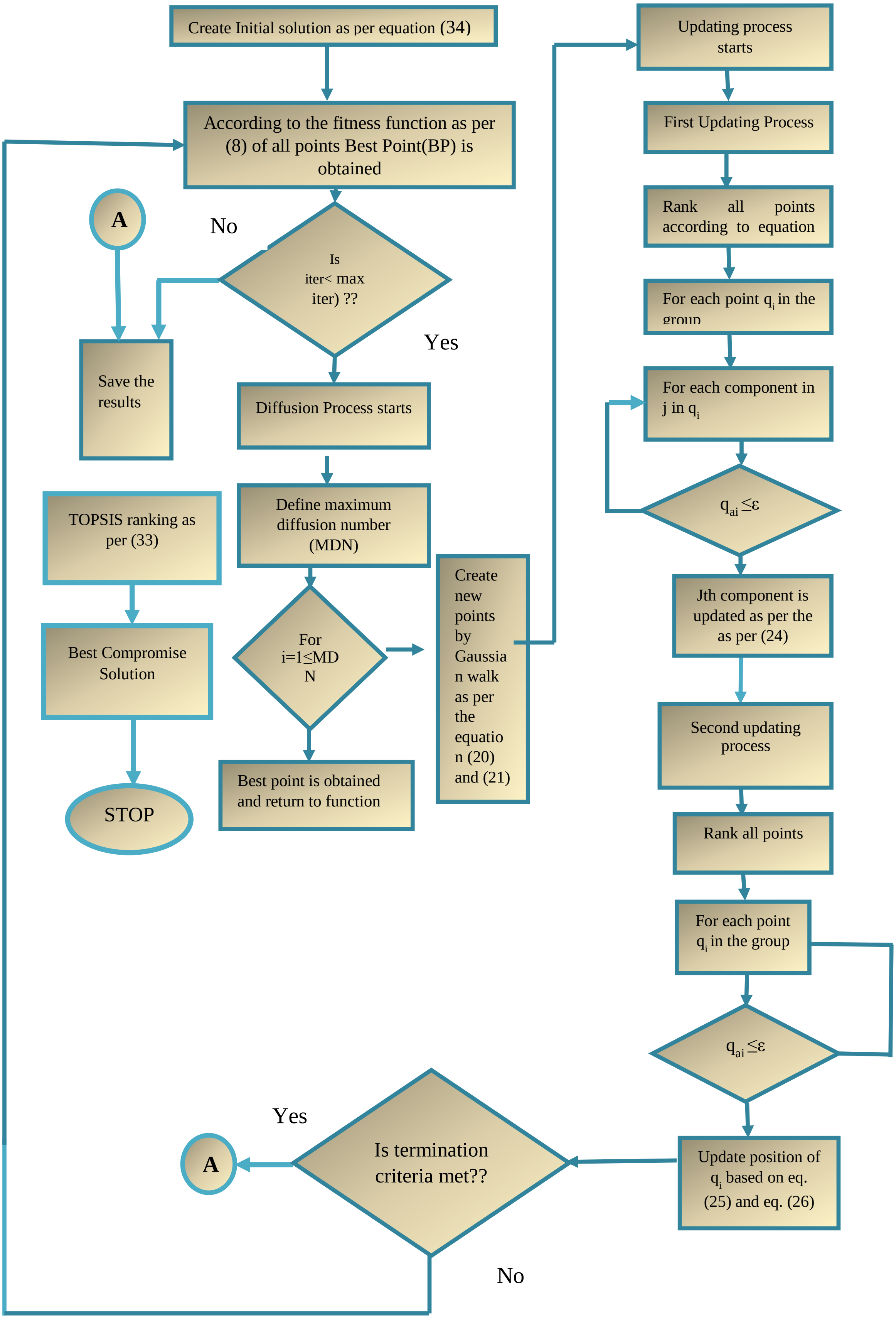

Fig.1. Implentation of flow chart of ISFSA in MOOD problem

VI. Implementation of ISFSA for Solution of Multi Objective Optimal Dispatch

In this section implementation of ISFSA is explained for economic emission dispatch problem. The step wise solution is given below.

Step-1 In this step all the random solution (Points) are evaluated as per the (34).

$$\text{Points}=P_i^{min} + \text{F}\times \left(P_i^{max} - P_i^{min}\right) \quad (34)$$

Where P_i^{max} and P_i^{min} are the maximum and minimum power limits of i^{th} generator and F is scale factor.

Step-2 Fitness of points generated in step-1 is calculated as per the (8) by satisfying all the operating constraints given by (9), (11) and(16). After ranking by (23) best points are evaluated according to their fitness.

The TOPSIS ranking is done as per (33) to get best compromise solution(BCS). For TOPSIS ranking single objective function is considered alone to minimized among the multi-objective function by assigning weight factor for that particular as 1 and for other objective remains zero. On the other hand, if all objective function among 'x' objectives required to be minimizes at a time, the weight assigned to each objective is considered as $1/x$.

Step-3 The best points obtained as in step 2 are diffused around its neighbouring position to generate other points in the search space as per (20) and (21).

Step-4 Fitness of diffused points of step-3 are evaluated again by (8) and has to satisfy operating constraints depicted in (9), (11) and(16) and re-ranking has been done.

Step-5 updating process is carried out by(24).

They are ranked again as in step-2, till the termination criterion has not been met, If the termination criterion is not met then from step-1 to step-5 are repeated again. Whole solution procedure is depicted using flowchart in "Fig. 1".

VII. Result and Discussion

In order to validate the potential ISFSA is applied to six different standard test systems. These optimization approaches are implemented using MATLAB R2009a and the system configuration is Intel core i5 processor with 2.20 GHz and 4 GB RAM.

A. Desescription Of Test Systems

1) Test system-1

It consists of six thermal generating units [7]. The fuel cost and emission function is convex in nature. Transmission losses are also taken into the account. The system demand is 1200 MW.

2) Test system -2

Here a solar plant with maximum power output of 50 MW and six thermal units are considered for analysis. Fuel cost, emission transmission loss and power demand are set as in test system 1.

3) Test system -3

In this test system having six thermal units, one solar power plant and one wind farm. The cost coefficient for wind farm considered as k_r =1, k_p=5, rated power output (P_{wind}^{R}) *as* 120 MW. The other constants are u_{ci}=5, u_{co}=45 and u_r=15. The shape and scale factor as 1 and 15 respectively. Fuel cost, emission, transmission loss and power demand are set similar to test system 1.

4) Test system -4

This test system has ten thermal units with valve point loading (VPL) effects. The entire Fuel cost, emission and B-loss coefficients data were adopted from [8]. Power Demand for this is 2000 MW.

5) Test system -5

In this test system there are ten thermal units with one solar power plant. Fuel cost, emission transmission loss and power demand are set as in test system 4. The solar power plant is same in test system -2.

6) Test system -6

This test system has ten thermal units, one solar power plant and one wind farm. The solar power plant is same as in test system -2. The data related to wind farm is similar to test case 3. Fuel cost, emission, transmission loss and power demand are set similar to test system 4.

B. Best Cost Solution

The optimum dispatch solutions for test system 1,2 and 3 in "Table 1.", and for test system 4,5 and 6 in "Table 2.". For test system 1, the outcome of simulation result obtained by SFSA and the proposed ISFSA in terms of best cost is found to be 63975.9724 $/hr and 63975.7780 $/hr respectively, the corresponding dispatch solution is presented in "Table 1.".

Table 1. Optimum dispatch solution obtained by SFSA and ISFSA with power demand of 1200 MW

Units	Test system-1		Test system-2		Test ststem-3	
	SFSA	ISFSA	SFSA	ISFSA	SFSA	ISFSA
P1	81.1157	80.7540	60.1524	59.6993	45.3875	45.1369
P2	87.3417	87.6918	55.4594	55.8831	34.4775	34.0697
P3	209.9996	209.9999	209.9999	209.9999	193.2754	194.3031
P4	224.9998	224.9999	224.9952	224.9999	195.8479	197.2366
P5	324.9984	324.9999	324.9961	324.9999	325.0000	325.0000
P6	324.9991	324.9999	324.9880	324.9999	323.5296	324.9995
P_{PV}	N. A	N. A	49.9521	49.9521	49.9521	49.9521
P_{wind}	N. A.	N. A.	N. A.	N. A.	116.0625	111.7116
TC($/hr)	N.A.	N.A.	N. A	N. A	60797.1464	60796.6458
C_{under}	N. A	N. A	N. A	N. A	7.2533	15.5508
C_{over}	N. A	N. A	N. A	N. A	239.3079	225.8507
Th. C ($/hr)	63975.9724	63975.7780	60762.0532	60761.7053	60550.5852	60555.2443
Emission(ton/hr)	1360.03320	1360.0657	1311.1350	1311.217	1176.6295	1184.9758
P_L (MW)	53.4498	53.4460	50.54258	50.5349	83.5325	82.4095

TC:Total Cost,Th. C: Thermal Cost, NA: Not Applicable

The results have been compared with Differential Evolution (DE) [3], Quasi –oppositional Teacher Learner based Optimization (QTLBO) [7] and most recently reported method Backtracking Search Algorithm (BSA) [10] and presented in "Table 3.". Here it is observed that the best cost solution obtained by SFSA is also found to be better than other reported method. Also comparing test system 1 and 2 i.e. with integration of solar power the operating cost reduced by 5.02% and while comparing test system 1 and 3 i.e. by integration of both solar and wind power operating cost reduced by 4.97%.

Similarly, for test system 4, outcome of simulation results by SFSA and ISFSA have compared with results reported using (QTLBO) [7], RCCRO [9] and (BSA) [10]. Here also results obtained by ISFSA are found to be superior. While comparing test system 4 and 5, test system 4 and 6 the total operating cost reduced by 2.97% and 5.18 % respectively.

Table 2. Optimum dispatch solution obtained by SFSA and ISFSA with power demand of 2000 MW

Units	Test Case-4		Test Case-5		Test Case-6	
	SFSA	ISFSA	SFSA	ISFSA	SFSA	ISFSA
P1	55.0000	55.0000	54.9875	55.0000	55.0000	55.0000
P2	80.0000	80.0000	79.9970	80.0000	78.9443	78.9081
P3	106.9412	106.9369	94.8682	94.6362	82.1450	82.1833
P4	100.5775	100.5775	87.5323	87.6698	74.5782	74.5407
P5	81.4969	81.5011	71.4956	71.4964	61.3737	61.3689
P6	83.0231	83.0233	70.0844	70.0000	70.0000	70.0000
P7	300.0000	300.0000	298.0291	297.9021	264.7241	264.6792
P8	340.0000	340.0000	336.7483	337.0262	298.2191	298.4907
P9	470.0000	470.0000	469.9966	470.0000	457.0549	456.8658
P10	470.0000	470.0000	469.9886	470.0000	469.9998	470.0000
P_{PV}	N. A.	N. A.	49.9521	49.9521	49.9521	49.9521
P_{wind}	N. A	N. A	N. A	N. A	120.0000	120.0000
TC ($/hr)	N.A.	N.A.	N.A.	N.A.	105715.4103	105715.3996
C_{under}	N. A	N. A	N. A	N. A	0.0000	0.0001
C_{over}	N. A	N. A	N. A	N. A	251.7421	251.7419
Th. C($/hr)	111497.6308	111497.6225	108185.5777	108185.4127	105463.6682	105463.6576
Emission ton/hr)	4572.1869	4572.1854	4398.6985	4399.1084	3782.8370	3782.8586
P_{loss} (MW)	87.0388	87.0388	83.68291	83.6828	81.9912	81.9888

Table 3. Comparison of results in terms of best cost solution

Method	Test sytem-1		Test sytem-4	
	Best Cost Solution			
	Cost ($/h)	Emission (ton/h)	Cost ($/h)	Emission (ton/h)
DE [3]	64083.0000	1345.6000	NA	NA
QTLBO[7]	63977.0000	1360.1000	111498.0000	4568.7000
BSA [10]	63976.0000	1360.1000	111497.6308	4572.1939
RCCRO[9]	NA	NA	111497.6319	4571.9552
SFSA	63975.9724	1360.03320	111497.6308	4572.1869
ISFSA	63975.7780	1360.0657	111497.6225	4572.1854

C. Best Emission Solution

Optimum dispatch solution corresponding to best emission obtained by SFSA and ISFSA have been presented in “Table 4.” for test system 1,2 and 3 and in “Table 5” for test system 4, 5 and 6 respectively. The comparison of results have made with different reported method as Differential Evolution (DE) [3], Quasi – oppositional Teacher Learner based Optimization (QTLBO) [7] and most recently reported method Backtracking Search Algorithm (BSA) [10] for test system 1 and presented in “Table 6.”.

Also results are compared with QTLBO [7], BSA [10] and RCCRO [9] for test system-4. In both the test systems results obtained by ISFSA are found to be superior to other methods. Comparing test system 1 and 2, test system 4 and 5 it is observed that the total emission reduced by 4.87% and 9.14 % respectively by solar thermal integration. While Comparing test system 1 and 3, test system 4 and 6 there is much reduction in total emission by 16.62% and 22.46% by integrated solar-wind thermal power generating system.

Table 4. Optimum emission solution obtained by SFSA and ISFSA with power demand of 1200 MW

Units (MW)	**Test Case-1**		**Test Case-2**		**Test Case-3**	
	SFSA	**ISFSA**	**SFSA**	**ISFSA**	**SFSA**	**ISFSA**
P1	124.9997	124.9999	124.9808	124.9996	124.9999	125.0000
P2	149.9974	150.0000	149.9448	149.9995	149.9998	149.9999
P3	201.1010	201.4089	190.8899	189.9192	171.8504	171.7912
P4	199.6312	199.2479	188.2610	188.0065	170.4498	170.4243
P5	287.5393	287.9689	270.03172	272.1069	246.0136	246.01885
P6	286.8925	286.5307	271.6166	270.7150	244.9751	244.9866
$\boldsymbol{P_{PV}}$	N. A	N. A	49.9521	49.9521	49.9521	49.9521
$\boldsymbol{P_{wind}}$	N. A.	N. A.	N. A.	N. A.	120.0000	120.0000
$\boldsymbol{C_{under}}$	N. A	N. A	N. A	N. A	0.0000	0.0000
$\boldsymbol{C_{over}}$	N. A	N. A	N. A	N. A	251.7421	251.7420
TC($/hr)	N.A.	N.A.	N. A	N. A	63655.6045	63655.4192
Th. C($/hr)	65994.9958	65992.4503	63279.6550	63289.8680	63403.8624	63403.6771
Emission(ton/hr)	1240.7033	1240.6545	1127.5775	1127.22010	962.0030	962.0028
P_{Loss}(MW)	50.1143	50.1565	45.6415	45.6932	78.2407	78.2426

D. Best Compromise Solution (BCS) and Pareto Optimal Solution

The Cost and emissions are now simultaneously optimized with equal weight to both objectives. In this paper, the two objectives were selected on the basis of TOPSIS ranking using (35). A large number of Pareto optimal solutions were obtained for MOOD problem. They are plotted in “Fig. 2” for two objectives at a time for test system 1 to 3 and in “Fig. 3” for test system 4 to 6.

The BCS using ISFSA and TOPSIS is found to be 64672.55911 $/hr, 1295.37772 ton/hr and 112821.97420 $/hr, 4185.30993 ton/hr for test system 1 and test system 4 respectively. Also comparison of results is made with DE [3], QTLBO [7], BSA [10], RCCRO [9] for respective test system and presented in “Table 7.”.

Table 5. Optimum emission solution obtained by SFSA and ISFSA with power demand of 2000 MW

Units (MW)	**Test Case-4**		**Test Case-5**		**Test Case-6**	
	SFSA	**ISFSA**	**SFSA**	**ISFSA**	**SFSA**	**ISFSA**
P1	54.9999	55.00000	54.99994	55.0000	54.9868	55.0000
P2	79.9998	80.00000	78.98101	79.2937	73.0167	73.4449
P3	81.1360	81.13442	79.03569	79.1279	72.2334	73.2071
P4	81.3664	81.36366	78.84822	79.3611	73.2677	73.3615
P5	159.9999	160.00000	159.99958	160.0000	159.9651	160.0000
P6	239.9999	240.00000	239.99987	240.0000	239.9998	240.0000
P7	294.5061	294.48525	279.00572	282.6587	249.8656	251.5241
P8	297.2489	297.26931	284.47932	284.9692	251.4523	251.6608
P9	396.7685	396.76604	386.22658	384.0072	367.9356	364.2236
P10	395.5690	395.57647	385.76835	382.8394	362.5558	362.7982
$\boldsymbol{P_{PV}}$	N. A.	N. A.	49.9521	49.9521	49.9521	49.9521
$\boldsymbol{P_{wind}}$	N. A	N. A	N. A	N. A	119.9976	120.0000
TC ($/hr)	N.A.	N.A.	N.A.	N.A.	111302.6126	111313.3125
$\boldsymbol{C_{under}}$	N. A	N. A	N. A	N. A	0.0043	0.0000
$\boldsymbol{C_{over}}$	N. A	N. A	N. A	N. A	251.7345	251.7420
Th.C ($/hr)	116412.5449	116412.44313	113369.06395	113391.0302	111050.8738	111061.5705
Emission (ton/hr)	3932.1990	3932.19893	3742.65330	3742.4830	3286.5676	3286.3592
Ploss	81.5957	81.5952	77.29533	77.2093	75.2285	75.1723

Table 6. Comparison of best emission solution

Method	Test sytem-1		Test sytem-4	
	Best emission solution			
	Cost ($/h)	Emission (ton/h)	Cost ($/h)	Emission (ton/h)
DE [3]	65991.0000	1240.7000	NA	NA
QTLBO[7]	65992.0000	1240.7000	116412.0000	3932.2000
BSA[10]	65992.0000	1240.6000	116412.4441	3932.2432
RCCRO[9]	NA	NA	116412.4441	3932.2433
SFSA	65994.9958	1240.7033	116412.5449	3932.1990
ISFSA	65992.4503	1240.6545	116412.4431	3932.1989

Table 7. Comparison of best compromise solution

Method	Test sytem-1		Test sytem-4	
	Best compromise solution			
	Cost ($/h)	Emission (ton/h)	Cost ($/h)	Emission (ton/h)
DE [3]	64843.0000	1286.0000	NA	NA
QTLBO[7]	64912.0000	1281.0000	113460.0000	4110.2000
BSA [10]	64766.8227	1289.5856	113126.7514	4146.0000
RCCRO[9]	NA	NA	113355.7454	4121.0684
ISFSA	64672.5591	1295.3777	112821.9742	4185.3099

Table 8. Optimum dispatch solution for best compromise solution obtained by ISFSA and TOPSIS with power demand of 1200 MW

UNIT(MW)	Test Case-1	Test Case-2	Test Case-3
	ISFSA	ISFSA	ISFSA
P1	101.8850	81.6882	74.6999
P2	114.3664	87.8004	78.1106
P3	208.0462	203.8795	189.8932
P4	207.7425	204.2947	189.5119
P5	311.4096	312.3881	290.7455
P6	308.4191	308.6688	288.4332
P_{PV}	N. A.	49.9521	49.9521
P_{wind}	N. A	N. A	120.0000
C_{under}	N. A	N. A	0.0001
C_{over}	N. A	N. A	251.7419
Total Cost($/hr.)	N.A.	N. A	61227.9677
Thermal Cost ($/hr.)	64670.2559	61193.8879	60976.2257
Emission(ton/hr.)	1295.5246	1227.6890	1054.8410
P_L(MW)	51.8710	48.6696	81.3464

Table 9. Optimum dispatch solution for best compromise solution obtained ISFSA and TOPSIS with power demand of 2000 MW

Units	Test Case-4	Test Case-5	Test Case-6
P1	55.0000	55.00000	55.0000
P2	80.0000	80.00000	76.9375
P3	86.3390	83.81089	77.6008
P4	84.6266	82.1782	75.9967
P5	130.0995	128.7719	117.0431
P6	147.7002	145.5013	129.5793
P7	300.0000	292.4820	266.6872
P8	319.5752	310.7495	280.3779
P9	439.1793	424.5143	412.8025
P10	442.0893	427.1345	416.4886
P_{PV}	N. A	49.9521	49.9521
P_{wind}	N. A	N. A	120.0000
C_{under}	N. A	N. A	0.0000
C_{over}	N. A	N. A	251.7420
Total Cost($/hr)	N.A.	N.A.	106628.0411
Thermal Cost($/hr)	112821.9742	109674.9568	106879.7832
Emission(ton/hr)	4185.3099	3976.3318	3494.2613
$P_{L(MW)}$	84.6096	80.09498	78.4657

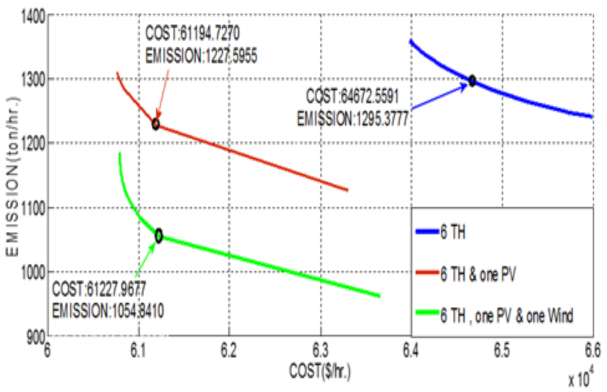

Fig.2. Optimal pareto front for test system-1, 2 and 3 obtained by ISFSA.

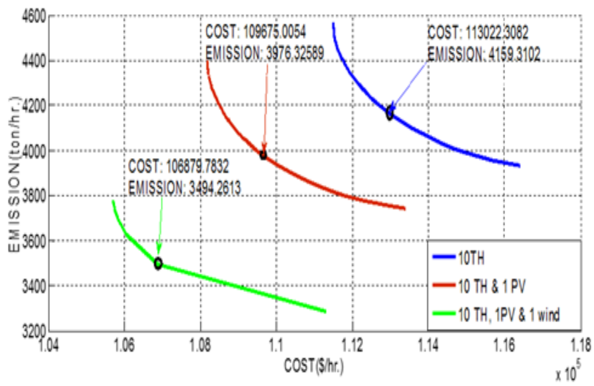

Fig.3. Optimal pareto front for test system-4, 5 and 6 obtained by ISFSA.

VII-A. Selcetion of Parameter

As SFSA is a heuristic method, it also requires optimal tuning parameter to discover global optima solution. In order to investigate best optimal tuning parameter of SFSA, it is applied on the test system-4 having 10-unit test system with non convex fuel cost characteristic due to VPL effect. Twenty-five independent run were conducted with different start point (NP) and maximum diffusion number (MDN). The statistical results are tabulated in “Table.10.”. Here it is observed that optimum cost is achieved by NP=50 and MDN=2 with comparatively low standard deviation (SD) of 0.0033, therefore selected for simulation analysis.

Further considering NP=50, MDN=2 simulation analysis was carried out by variation in scale factor on the same 10-unit test system over 25 repeated trails. The outcome of simulation result is tabulated in “Table 11(a).”. Here it is observed that results in terms of cost, standard deviation and also the CPU time get improved with respect to SFSA technique. Comparison of convergence characteristics of SFSA and ISFSA is shown in “Fig. 4”. Also the convergence characteristics of ISFSA for thermal, solar-thermal and solar-wind-thermal system described above as test system 4, 5 and 6 is plotted in “Fig 5”

Table 10. Determination of optimal tuning parameter for SFSA

NP	MDN	Min Cost ($/hr.)	Ave Cost ($/hr.)	Max Cost ($/hr.)	S.D	Ave CPU time (sec)
25	2	111497.6949	111497.8336	111498.0992	0.1508	5.41
	4	111497.6770	111497.8173	111497.9498	0.0862	9.83
	6	111497.6874	111497.8286	111498.1284	0.1449	10.56
50	2	**111497.6308**	**111497.6349**	**111497.6425**	**0.0033**	11.66
	4	111497.6525	111497.7004	111497.7459	0.0299	16.54
	6	111497.6451	111497.6805	111497.7298	0.0296	23.31
100	2	111497.7189	111497.7820	111497.8846	0.0532	25.28
	4	111497.6854	111497.7596	111497.8711	0.0519	35.57
	6	111497.6688	111497.7786	111497.8979	0.0677	38.66

Table 11(a). Effect of Scale factor (F)

F	Min Cost ($/hr.)	Ave Cost ($/hr.)	Max Cost ($/hr.)	S.D	Ave CPU time (sec)
0.3	111497.6741	111497.7233	111497.8003	0.0517	11.82
0.4	111497.6470	111497.6815	111497.7230	0.0308	11.62
0.5	**111497.6225**	**111497.6324**	**111497.6350**	**0.0023**	**11.42**
0.6	111497.6478	111497.6818	111497.7190	0.0252	11.72
0.7	111497.6619	111497.6938	111497.7741	0.0459	11.63

F: Scale Factor

Table 11(b). Comparison of results obtained by ISFSA with SFS for test system 4

Method	Min Cost ($/hr.)	Ave Cost ($/hr.)	Max Cost ($/hr.)	S.D	Ave CPU time (sec)
SFSA	111497.6308	111497.6349	111497.64250	0.0033	11.66
ISFSA	111497.6225	111497.63242	111497.63509	0.0023	11.42

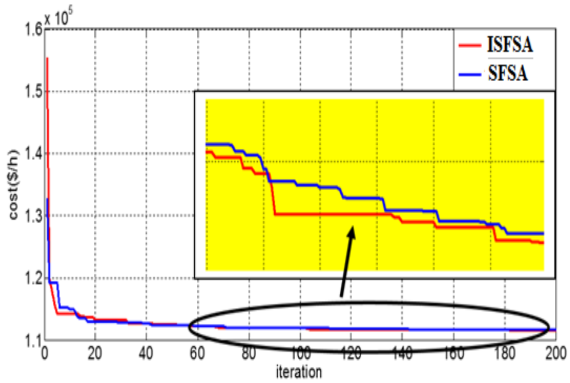

Fig.4. Comparison of convergence characteristics of SFSA and ISFSA for test system 4

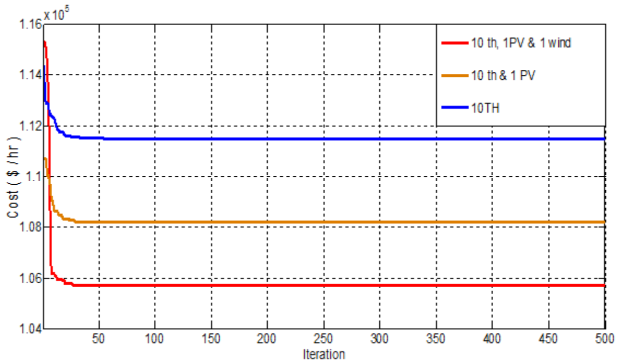

Fig.5. Convergence characteristic for test system-4, 5 and 6

VII-B. Computational Efficiency

The simulation time of SFSA and proposed ISFSA algorithms is compared for all six test cases in “Fig. 6”. Considering complexity of test systems, the CPU time in rage of 6 to 12 seconds is obvious.

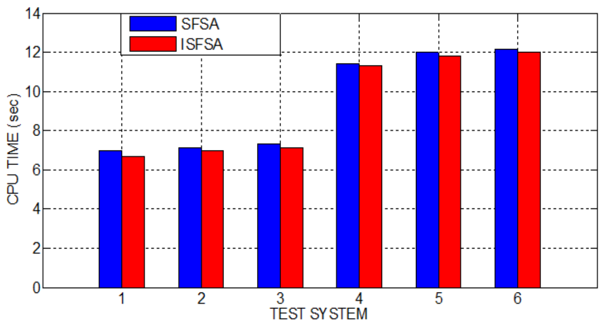

Fig.6. Average CPU time of ISFSA algorithm for different test systems

VIII. Conclusion

The paper proposed a novel improved stochastic fractal search for solution of MO problem of solar-wind-thermal system. The problem under consideration is solved for the simultaneous minimization of multiple objectives as cost and emission using a powerful newly proposed search technique, SFSA, which mimics the phenomenon of natural growth called fractal. A user defined scale factor is utilized to improve the exploration and exploitation capability of SFSA. The proposed ISFSA method effectively tackles complex practical constraints of thermal generation, and effect of WP uncertainty. The effect of solar, wind power integration on cost as well as emissions is also investigated. ISFSA produces the best results as compared to other recent reported methods for the tested problems. Finding the best solution for a MO problem is difficult as there are multiple attributes to consider, and therefore some kind of aggregation is necessary to reflect the merit of a solution. Many indices, based on different concepts, are available; however, each provides a different result. In this paper TOPSIS ranking index is considered for comprehensive merit criterion of the MO solar-wind-thermal system problem.

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APPENDIX-A

β=-4.7e-3, η_r =0.105, η_2 =0.9, T_{ref} =25 ℃ , P_f =0.9, A=90363.04m^2

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