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Bio-Inspired Bird Swarm Algorithm for Solving Economic Load Dispatch Problems

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Abstract- The power system need to be operated economically and with cost efficiency. In this paper application of new bio-inspired metaheuristic named as Bird Swarm Algorithm (BSA) has been adopted for the optimization of ELD problems in power system operation. The concept has been conceived from the flocking behavior of birds. Birds mainly have three kinds of behaviors i.e. foraging behavior, vigilance behavior and flight behavior. Therefore by the implementation of social behavior, social interaction and swarm intelligence, BSA has been formulated for economic load dispatch problems.

1. Introduction

Power system need to be operated economically to make the electrical energy cost-effective to the consumer in the face of constantly growing size of power grid, huge demand and the energy crises across the world. Economic Load Dispatch (ELD) is the process of allocating optimum generation values to the generating units so that the system load is supplied entirely and most economically. Primary objective of economic load dispatch problem is to minimize the cost of generation while honoring the operational constraints of available generation sources.

Till date, various investigation on ELD have been undertaken, researchers have proposed several optimization techniques which are classified in to two category i.e. conventional and unconventional or evolutionary approaches. The continuously differentiable problems can be attacked by conventional methods which are deterministic approaches such as Lagrange multiplier (LM), Linear programming (LP) and dynamic programming (DP).But in practice, input-output characteristics of modern generating units are highly nonlinear due tovalve point loadings, ramp rate limits and multi-fuel options. Modern economic load dispatch problems are more complex constrained optimization problem because of its highly non-linear, non-convex objective function having multiple local optima and a large number of equality and inequality constraints of the generators and the system. Conventional approaches are failed to solve such complex problem since they are problem specific, cannot deal with highly non-linear and non-convex optimization problem efficiently and sometimes get trap in their local searches.

In the recent years, more interest have been focused on developing the evolutionary optimization techniques[1] which are stochastic in nature and are biologically inspired. These inspirations come from the behavior of birds, insects, fishes, ants, bees and natural phenomenon such as evolution, gravity. Therefore the non-convex, non-smooth and non-differentiable ELD problems are addressed by the population based modern intelligent stochastic methods including improved evolutionary programming (EP)[2], particle swarm optimization (PSO)[3], differential evolution (DE)[4], artificial bee colony (ABC)[5], backtracking search optimization (BSA) [6],bacterial foraging optimization (BFO)[7], biogeography based optimization (BBO)[8] ,harmony search (HS)[9], group search optimizer (GSO)[10], firefly algorithm (FA)[11], differential harmony search (DHS)[12], krill herd algorithm (KHA) [13],chaotic bat algorithm (CBA)[14], improved PSO[15], improved DE [16], simulated annealing (SA)[17],

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tabu search [18], ant colony optimization (ACO)[19], chaotic ant swarm optimization (CASO) [20], modifiedartificial bee colony (MABC)[21], modified flower pollination algorithm (MFPA) [22], cuckoo search (CS)[23],[24], kinetic gas molecule optimization (KGMO) [25], grey wolf optimization (GWO) [26], social spider algorithm (SSA) [27], greedy randomized adaptive search procedure (GRASP)[28]etc.

Researchers have also proposed some hybrid algorithms for modern ELD problem by combining two or more nature inspired techniques such as PSO-DE[29], GA-BFO [30], PSO-GSA[31], [32], CPSO-SQP [33] etc. Application of hybrid algorithm gives highly competitive results.

This paper presents the application of new bio-inspired metaheuristic Bird Swarm Algorithm (BSA) for the optimization of ELD problem. The inspiration comes from the flocking behavior of birds. Birds mainly have three kinds of behaviors i.e. foraging behavior, vigilance behavior and flight behavior. Therefore by the implementation of social behavior, social interaction and swarm intelligence, BSA is formulated for optimization of complex problems.The content of the paper are organized as follows. Section 2 describes the implementation of Bird Swarm Algorithm for complex ELD problem. Section 3 provides the formulation of the ELD problem. Case studies, results and comparisons are discussed in section 4. Finally, we end the paper with some conclusion and future work in section 5.

II. ELD Problem Formulation

2.1 Objective function

The objective of the ELD problemis tominimize the total fuel cost of thermal power plants for a given load demand subject to all equality and inequality constraints. The various cost function used in ELD problem are ass follows.

2.2 Quadratic cost function:

The objective is to minimize the quadratic fuel cost function of the thermal units, given by

$$\min F=\sum_{i=1}^{n}F_i(P_i)=\sum_{i=1}^{n}a_i+b_iP_i+c_iP_i^2 \qquad (1)$$

Where,n is the total number of generating units,$F_i(P_i)$ is the fuel cost of the ith generating unit in \$/hr, P_i is the power generated by the ith generating unit in MW and a_i, b_i and c_i are cost coefficients of ith generator.

2.3 Cost function with Valve point loading effect:

It is necessary to adjust the fuel input supplied to the prime mover of the generator to satisfy the sudden increase and decrease in power demand. In order to achieve this fuel admission valves are frequently opened and closed according to the load curve, this increases the throttling losses rapidly and rise in incremental heat rate suddenly. The fuel admission through the valve in turbine shows the rippling effect in the normal fuel cost curve as shown in figure. By adding the sinusoidal component to the normal fuel cost equation that makes the traditional power dispatch problem to be non – convex as given below,

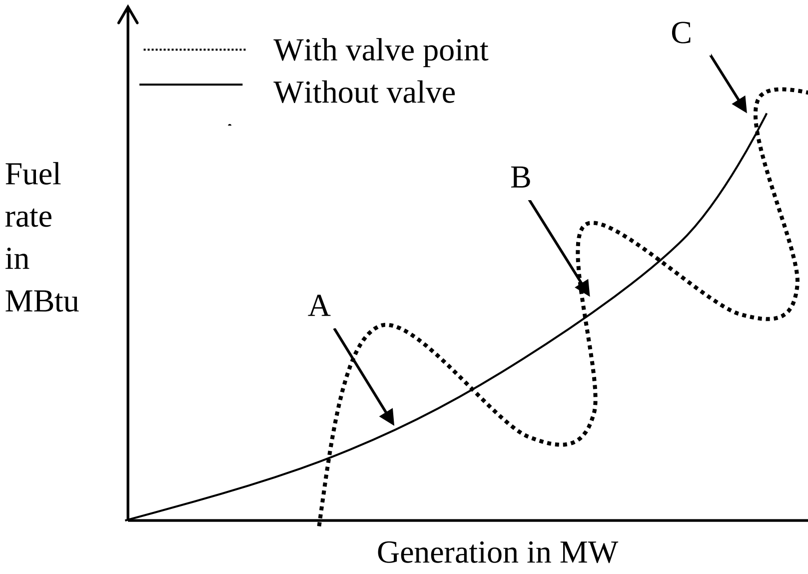

Figure 1. Valve point loading curve

The objective function when the valve-point loading effect is taken into account becomes:

$$\min F=\sum_{i=1}^{n}F_i(P_i)=\sum_{i=1}^{n}(a_i+b_iP_i+c_iP_i^2)+\left|e_i\sin\left(f_i\left(P_i^{min}-P_i\right)\right)\right| \qquad (2)$$

Where, e_i and f_i are coefficient of the valve-point effect of generators.

2.5 Optimization constraints

The equality and inequality constraints for the ELD problem are the real power balance criterion, real power generation limits, ramp rate limit, and prohibited operating zones as given by the following equations:

Power balance uniformity constraints:

The total power generation by thermal units must be equal to the total power demanded by load and total transmission loss. It may be mathematically formulated as follow:

$$\sum_{i=1}^{n} P_i = P_D + P_L$$

Where, P_D is the total power demand in MW, P_L represents the line losses in MW which is calculated using B-coefficients, given by

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j$$

Where, P_i is the generation of the ith generating unit inMW.$P_i$andP_j are the real power injection at ith and jth buses, respectively, and B_{ij} , is the loss coefficients which can be assumed to be constant under normal operating conditions.

Generation capacity constraints:

The generated power should be within its lower and upper limits given as:

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

P_i^{min}andP_i^{max} are the minimum and maximum power generation limits of the ith generator.

Ramp Rate Limit(RRL)constraints:

The Ramp rate constraint restricts the operating range of physical lower and upper limit to the effective lower limit and upper limit respectively. Thus, the operating limits are altered as follows:

$$\max(P_i^{min}, UR_i - P_i^0) \le P_i \le \min(P_i^{max}, P_i^0 - DR_i) \qquad (6)$$

Where $P_i$is the current power output of ith generating unit and P_i^0 is previous power output of the ith generating unit, UR_i and DR_i are the upper ramp and lower ramp limits of ith generator, respectively.

POZ (Prohibited operating zones) constraints:

Under practical situation, the whole of the unit operating range is not always available for operation. Units may have prohibited operating regions [34] due to physical operational limitations that are amplified vibrations in a shaft bearing in a certain operating regions, faults in the machines or associated auxiliaries, such as boiler, feed pump etc(3)The feasible operating zones of ith unit can be described as follows:

$$\left.\begin{array}{lll} P_i^{min} \le P_i \le P_{i,1}^{L} & & (i = 1, 2, \ldots\ldots n \\ P_{i,j-1}^{U} \le P_i \le P_{i,1}^{L} & (j = 2, 3, \ldots\ldots n_z) & (i = 1, 2, \ldots\ldots n \\ P_{i,n_z}^{U} \le P_i \le P_i^{max} & & (i = 1, 2, \ldots\ldots n \end{array}\right\} \qquad (7)$$

(4)

Where, $P_{i,j-1}^{U}$and $P_{i,1}^{L}$are the upper and lower boundaries of jth prohibited zone of ith unit and $n_z$is the number of prohibited zones of ith unit.

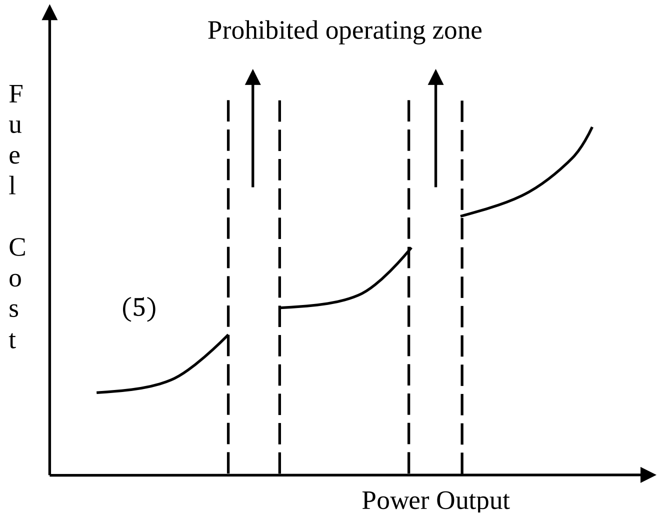

Figure 2: Input-output curve with prohibited operating zones.

III. Bird Swarm Algorithm

BSA is a new meta-heuristic swarm intelligence algorithm proposed by Xian-Bing Meng[35] , inspired by social behavior and interaction of birds. Different birds gather food in different ways. Foraging is the searching for food resources or gathering food either for immediate consumption or future storage. Birds forage in flocks because they gather more information in flocks than their own intelligence. Group foraging boost-up the chances of detecting predators. While foraging some birds keep vigilance and keep their eye on predation threat. Therefore birds would randomly choose between foraging and keeping vigilance. Birds have some kind of social interaction by which they communicate on detecting the predators, food patches and would fly off together. Therefore, moving in flocks results in higher foraging efficiency and better survival rate than a single one.

Birds in flock fly from one site to other for gathering food or escaping themselves from predators and they continue their searches for food at new site. Flocks feeding are categorized as producer and scroungers. Producers are searchers and scroungers are copier individuals. So scrounger appeared to rely on the producers to obtain the food items. Producers searching for one's food and scroungers searching for food discovered by others. In feeding group lowest reserve birds are scroungers while the one with high reserves would be producers. Thus the intelligence behavior of birds and their social interaction result into a new optimization algorithm i.e. Bird Swarm Algorithm to optimize the objective function.

Working criteria of BSA is as follow:

- It is a stochastic decision that each bird can switch between vigilance behavior and foraging behavior.
- During foraging, birds can keep record of their swarms previous best results and each bird can keep record and update of previous best experience and can share any kind of social information.
- The birds try to move at the center of swarm during vigilance. Birds with higher reserves are in the center of the swarm.
- Birds would fly to another site in search of food and during that birds may switch between producing and scrounging. Highest reserve birds are called Producers and lowest reserves are Scrounger.
- Producers are the ones who actively search the food and scroungers follow the producer for food.

Foraging behaviour (exploitation):

Each bird searches for food according to its experience and the swarm's experience can be explained as;

$$x_{i,j}^{t+1} = x_{i,j}^{t} + \left(P_{i,j} - x_{i,j}^{t}\right) * c1 * rand(0,1) + \left(g_j - x_{i,j}^{t}\right) * c2 * rand(0,1) \qquad (8)$$

Where j ϵ (1………D), rand (0, 1) denotes independent uniformly distributed numbers in (0, 1).

$c1$and$c2$ are two positive numbers, which can be respectively called as cognitive and social accelerated coefficients.

$P_{i,j}$is the best previous position of the ith bird and g_j the best previous position shared by the swarm.

If a uniform random number in (0, 1) is smaller than P (P∈ (0,1), a constant value, the bird would forage for food. Otherwise, the bird would continue vigilance.

Vigilance behaviour (exploration):

Birds try to save themselves from the predators attack by moving towards the centre of the swarm. In this way they try to compete with each other as the birds which are at the centre are much secured than those at the outer periphery. Thus, each bird would not directly move towards the centre of the swarm. These motions can be formulated as follows;

$$x_{i,j}^{t+1} = x_{i,j}^{t} + A1\left(mean_j - x_{i,j}^{t}\right) rand(0,1) + A2\left(P_{k,j} - x_{i,j}^{t}\right) * rand(-1,1) \qquad (9)$$

$$A1 = a1 * \exp\left(\frac{Pfit_i}{Sumfit + E} * N\right)$$

$$A2 = a2 * \exp(\left(\frac{pfit_i - pfit_k}{|pfit_k - pfit_i| + E}\right) \frac{N * pfit_K}{Sumfit + E})$$

Where *k (k ≠i)* is a positive integer, randomly chosen between *1* and *N*. $a1$and$a2$ are two positive constants in [0, 2],

$pfit_i$,denotes the i^{th}bird's best fitness value and $Sumfit$represents the sum of the swarm's best fitness value. *E*, which is used to avoid zero-division error, is the smallest constant in the computer. $mean_j$, denotes the j^{th} element of the average position of the whole swarm.

Flight behaviour (exploration and exploitation):

Birds after foraging on their previous site would try to move to a different site in search of more food and also to save themselves from the predator's attack. The two flight groups are producers and scroungers in which producers try to search for food and scroungers are the group of members who depends on the food found by the producers. The behaviours of the producers and scroungers can be described mathematically as follows, respectively:

$$x_{i,j}^{t+1} = x_{i,j}^{t} + randn(0,1) * x_{i,j}^{t} \tag{10}$$

$$x_{i,j}^{t+1} = x_{i,j}^{t} + \left(x_{k,j}^{t} - x_{i,j}^{t}\right) * FL * rand(0,1) \tag{11}$$

where $randn(0,1)$ denotes Gaussian distributed random number with mean 0 and standard deviation 1, $k\epsilon[1,2,3\ldots\ldots N]$, $k \neq i$, $FL(FL \in [0,2])$,means that the scrounger would follow the producer to search for food.

For simplicity, we assume that each bird flies to another place every FQ unit interval. Here, FQ is a positive integer.

The BSA shows good diversification by birds' vigilance behavior and producers' behavior. BSA has four searching strategies as mentioned above by which they find a perfect balance between exploration and exploitation.

BSA can be summarized as follow:

Step 1: Number of birds or search agents is considered as population size N.

Step 2: Initiate the position vector of each individual for flying and foraging. Initialize maximum number of iteration and also define the related parameters.

Step 3: Evaluate the fitness value of N individual and find the best solution.

Step 4: Generate the new position by using four searching strategies as mentioned through equation 1-4. And find the fitness for new generated position.

Step 5: Check whether the new generated solution are better than the previous ones and update them.

Step 6: Repeat the step 3-5 until they find the best fitness value.

Step 7: The termination is done when a maximum number of iteration met.

VI. Implementation of BSA To ELD Problem

In this section, the BSA algorithm is implemented to solve the different types of ELD problems. The various steps of solving the ELD problem using BSA are described below:

Step1: Initialization of population N, each comprising Ng number of generating units and define the related parameters a1, a2, FQ, c1, c2.

Step2: Generation values of each generating units is randomly initialized within their lower and upper operating limits except the last unit. The generation value of last unit is evaluated using equation (3). The infeasible solutions that violated the constraints are reinitialized. The position matrix is created as follow:

$$\mathrm{P} = \begin{bmatrix} \mathrm{P}_1^1, & P_2^1, & \cdots & P_{Ng}^1 \\ P_1^2, & P_2^2, & \ldots & P_{Ng}^2 \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \ldots & \vdots \\ \vdots & \vdots & \ldots & \vdots \\ P_1^N, & P_2^N, & \ldots & P_{Ng}^N \end{bmatrix}$$

Step3: Calculate N individual fitness value of all the birds using objective function from the equations (1-2) and find the best solution.

Step4: Evaluate foraging, vigilance and flight behavior of birds using equations 8, 9, 10 and 11 and new positions are generated using the four searching strategies.

Step5: The new solutions are checked for various constraints using equations (3-7). If any power generation value is less than the minimum level it is made equal to minimum value and if it crosses the maximum limit it is set to maximum value. If the new solutions are better than the previous ones and not violating any constraints, update them.

Step6: Repeat the step 3-5 until they reached the last iteration.

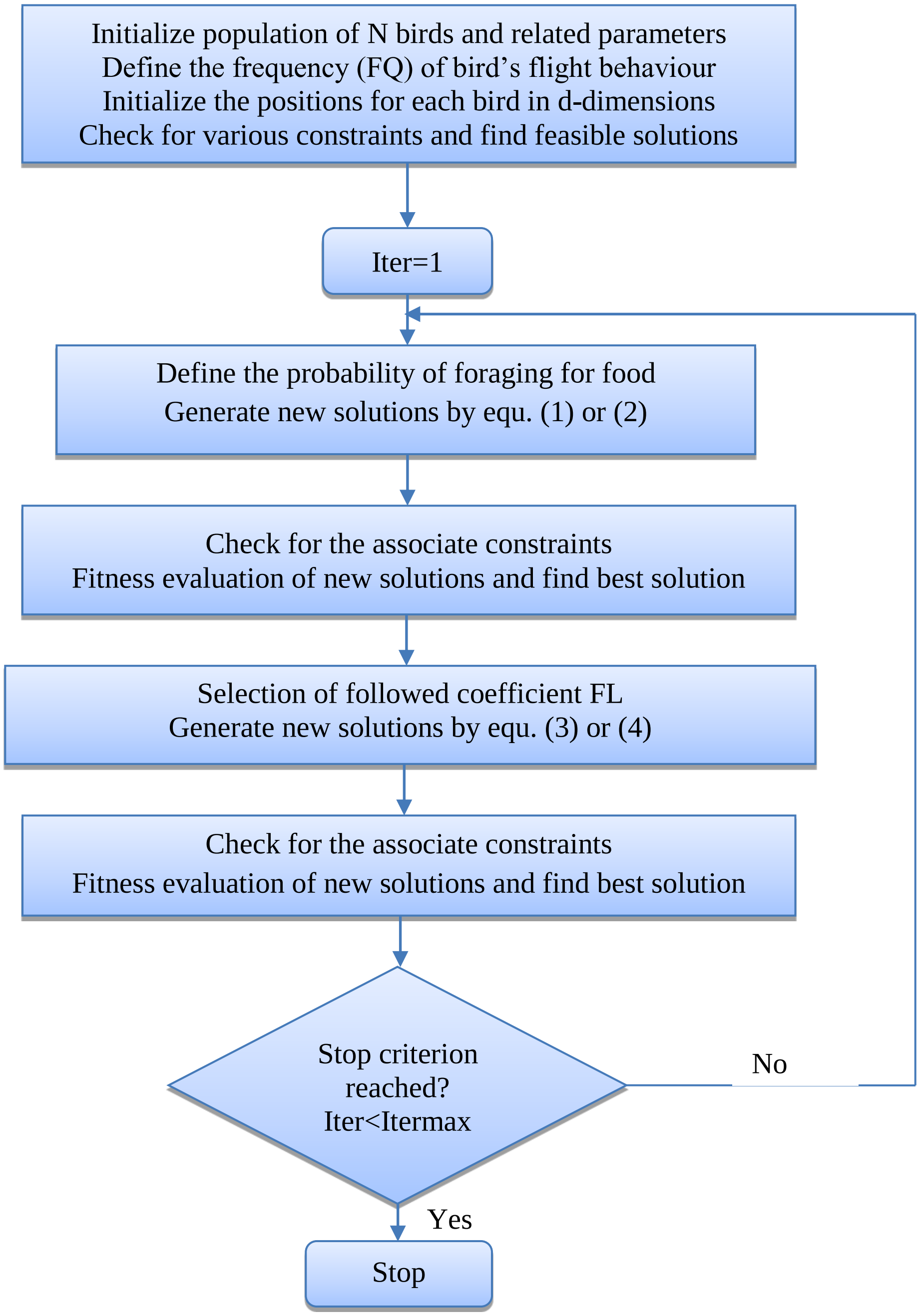

Figure 3. Flow Chart of BSA For ELD Problems

V. Results and Analysis

Selection of BSA parameters:

Set of control parameters can be found by trial and error, usually by performing number of experiments with different values. Parameters that best fit each problem have to be chosen carefully. In BSA there are number of parameters that affect the best fitness value of objective function and convergence rate for that problem like population size, maximum number of iteration, cognitive accelerated coefficient, social accelerated coefficient, a1, a2 and FQ. Table I& II summarizes the optimal control parameters of BSA obtained by the tuning process.

Maximum number of iteration is taken to be 250.Initially the number of birds is fixed at 30 and parameters a1 & a2 is varies from 0.1 to 2.0 in various steps. The results are taken over 5 independent trials. It is observed from the table-I that minimum cost/hr obtained for this test is 15442.6646 for population size of 100 and a1 & a2 1.

C1 and C2 are the cognitive and social accelerated coefficient. C1Є [0.5,5.0], C2 Є [0.5,5.0], considering population size to be 100 and a1,a2 1. Again the numbers of trail are performed for different values of c1 and c2. The minimum cost/hr obtained is 15442.6612 for C1 2 and C2 2. All the simulations for BSA are performed on the personal computer with an Intel core i5 processor @ 2.40 GHz and 8.0 GB of RAM in window-10, 64-bit operating system. Final selections of parameters for all test cases are reported in table-III.

Table-I Effect Of Parameters Of BSA On Optimum Generation Cost

Population size	**a1&a2**	**Minimum**	**Mean**	**Maximum**	**SD**
30	0.1	15443.1016	15446.5357	15449.9735	4.0455
	0.5	15443.0782	15444.2432	15447.6061	1.972
	1.0	15443.0827	15444.4174	15447.5012	1.9047
	1.5	15442.9769	15443.9022	15447.9274	1.809
	2.0	15444.3203	15447.2790	15458.0668	6.165
50	0.1	15443.9827	15444.9905	15445.9005	1.3116
	0.5	15443.0123	15443.3980	15444.8144	0.8537
	1.0	15442.6772	15442.9825	15443.0062	0.468
	1.5	15442.7453	15443.5160	15444.4398	0.9767
	2.0	15442.7968	15442.8501	15443.1800	0.199
100	0.1	15442.7104	15442.7472	15443.8891	0.0830
	0.5	15442.6676	15442.7634	15442.8833	0.0828
	1.0	**15442.6646**	**15442.7722**	**15442.8566**	**0.0903**
	1.5	15442.6855	15443.1628	15444.7586	0.8943
	2.0	15442.7928	15443.3113	15445.8016	1.1143

Table-II Effect Of Change Of Cognitive And Social Accelerated Coefficient

C2 **C1**	**0.5**	**1.0**	**1.5**	**2.0**	**5.0**
0.5	15445.0524	15443.1910	15442.918	15442.8239	15442.7439
1.0	15443.8506	15462.2574	15446.358	15442.7456	15442.6970
1.5	15559.6489	15450.7065	15443.1190	15443.3804	15442.6748
2.0	15445.0757	15442.9022	15443.7505	**15442.6612**	15442.8514

Table-III Final Selections Of Parameters

Population size	**FQ**	**a1**	**a2**	***c*1**	***c*2**
100	10	1	1	2	2

Test cases:

Case I: 6-unit system with POZ, ramp rate limit and transmission losses.

Case II: 13-unit system including valve point loading effect without transmission losses.

Case III: 40-unit system with transmission loss including valve point loading effect is considered.

Case IV: 15-unit system with prohibited operating zones.

First test system with 6-generators:

The system consists of 6 thermal generating units. The total power demand on the system is 1263MW. The ramp rate limit, POZ and transmission losses are taken into consideration. Due to the increased complexity, non-linearity, it has more local minima and thus it becomes difficult to obtain global minima. The system coefficients for this test case are given in table-II. The B-loss coefficients are listed in [40]. The parameters of the algorithm for this test are reported in table-I. The optimum sharing of loads among generators obtained from BSA are compared with other KHA [13], CBA [14], DE [36], RDPSO [37], aBBOmDE[38], NPSO-LRS [39] algorithm as presented in table-II. It is obvious from the simulation resultsthat this algorithm provides the best solution in terms of minimum fuel cost, power losses without violating any constraints. Convergence characteristic for 6 unit system is reported in figure**.**

Table-IV Data Of EDP For 6-Unit Test System With Line Loss, POZ And Ramp Rate Limit

Unit (i)	P_i^{min}	P_i^{max}	a_i	b_i	c_i	UR_i	DR_i	P_i^0	POZs
1	100	500	240	7.0	0.0070	80	120	440	[210,240][350,380]
2	50	200	200	10.0	0.0095	50	90	170	[90,110][140,160]
3	80	300	220	8.5	0.0090	65	100	200	[150,170][210,240]
4	50	150	200	11.0	0.0090	50	90	150	[80,90][110,120]
5	50	200	220	10.5	0.0080	50	90	190	[90,110][140,150]
6	50	120	190	12.0	0.0075	50	90	150	[75,85][100,105]

Table-V Best solutions and comparison of statistical results of various methods for test case-1 with a demand of 1263 MW.

Unit/power output	**BSA**	**CBA[14]**	**KHA[13]**	**DE[36]**	**RDPSO[37]**	**ABBOmDE[38]**	**NPSO-LRS[39]**
P1	447.0999	447.4187	447.4150	448.27	445.2541	447.3944	446.96
P2	173.0451	172.8255	173.2917	172.96	172.7916	173.4968	173.3944
P3	263.8345	264.0759	263.3559	263.44	263.3163	263.2259	262.3436
P4	138.9975	139.2469	138.9646	139.3	138.0006	138.8915	139.5120
P5	165.4757	165.6526	165.3759	165.28	165.4104	165.1239	164.7089
P6	86.9627	86.7652	87.0417	86.68	87.07979	87.2793	89.0162
Total power output	1275.4154	1275.9848	1275.4449	1275.93	1275.446	1275.4121	1275.9351
P_{Demand}	1263	1263	1263	1263	1263	1263	1263
Ploss	12.4154	12.9848	12.4449	12.95	12.446	12.412	12.9351
Min. Cost ($/hr)	15,442.6623	15,450.2381	15,443.0752	15,449.5826	15,443.096	15,442.673	15,450.00
Mean cost ($/hr)	15,442.762	15,454.76	15,443.1863	15,449.6171	15,443.0964	15,442.83	15,450.50
Max. cost ($/hr)	15,442.893	15,518.6588	15,443.3265	15,449.6508	15,443.096	15,442.9930	15,452.00
SD	0.09075	2.965	NA	NA	NA	NA	NA

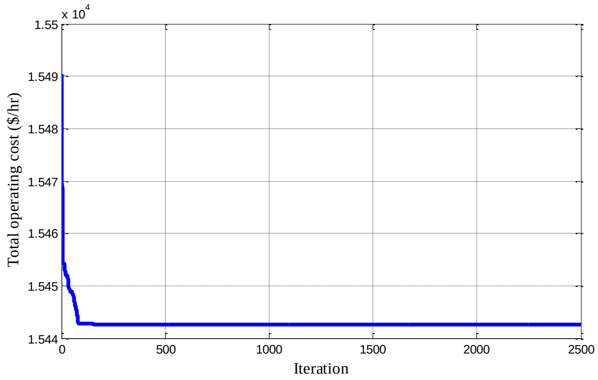

Figure:4. Convergence Characteristics Of BSA For The 6 Unit System With POZ And Ramp Rate Limit**.**

Second test system with 13-generators:

The system consists of 13 generating units with valve point loading effect is considered here. The complexity of the system has increased significantly with higher non-linearity. So it becomes difficult to obtain the global solution. The load demand of this test system is 1800MW. The parameters for this test are taken from table-I. The system coefficients for this test are reported in table-VI. The comparison of best, mean and worst cost/hrobtained by BSA with the results ofGRASP [28], CBA [14],SSA [27], DEL [4] and FA [11]recently proposed algorithms reported in various literatures are shown in table-VII. The convergence characteristic of the generation cost for 13 unit system using BSA is shown in figure-5. It can be observed that smooth convergence is obtained with BSA.

Table-VI Data Of EDP For 13-Unit Test System With Valve Point Loading Effect.

Unit (i)	P_i^{min}	P_i^{max}	a_i	b_i	c_i	e_i	f_i
1	0	680	550	8.10	0.00028	300	0.035
2	0	360	309	8.10	0.00056	200	0.042
3	0	360	307	8.10	0.00056	200	0.042
4	60	180	240	7.74	0.00324	150	0.063
5	60	180	240	7.74	0.00324	150	0.063
6	60	180	240	7.74	0.00324	150	0.063
7	60	180	240	7.74	0.00324	150	0.063
8	60	180	240	7.74	0.00324	150	0.063
9	60	180	240	7.74	0.00324	150	0.063
10	40	120	126	8.60	0.00284	100	0.084
11	40	120	126	8.60	0.00284	100	0.084
12	55	120	126	8.60	0.00284	100	0.084
13	55	120	126	8.60	0.00284	100	0.084

Table-VII Best Solutions And Comparison Of Statistical Results Of Various Methods For Test Case-2 With A Demand Of 1800MW**.**

Unit/power output	**BSA**	**GRASP[28]**	**CBA[14]**	**SSA[27]**	**DEL[4]**	**FA[11]**
P1	628.3185	628.3185	628.3185	628.3178	628.3185	628.31852
P2	149.5997	149.5949	149.5997	149.5731	149.5996	149.59952
P3	222.7491	222.7571	222.7491	224.3883	222.7490	222.74912
P4	109.8666	109.8660	109.8666	109.8665	109.8665	109.86655
P5	109.8666	60.0000	109.8666	109.8665	109.8665	109.86655
P6	109.8666	109.8661	109.8666	109.8659	109.8665	109.86655
P7	60.0000	109.8662	109.8666	109.8643	109.8665	109.86655
P8	109.8666	109.8665	60.0000	109.8664	60.0000	60.00000
P9	109.8666	109.8665	109.8663	60.0000	109.8665	109.86655
P10	40.0000	40.0000	40.0000	40.0000	40.0000	40.00000
P11	40.0000	40.0000	40.0000	40.0000	40.0000	40.00000
P12	55.0000	55.0000	55.0000	55.0000	55.0000	55.00000
P13	55.0000	55.0000	55.0000	55.0000	55.0000	55.00009
Total power output	1800	1800	1800	1800	1800	1800
P_{Demand}	1800	1800	1800	1800	1800	1800
Min. Cost ($/hr)	17,963.8293	17,960.393	17,963.8339	17,963.766	17,960.3661	17,963.8308
Mean cost ($/hr)	17963.86124	17,966.106	17,965.4889	-	17,966.1306	18,029.16
Max. cost ($/hr)	17,963.9005	17,968.868	17,995.2256	-	17,975.4109	18,168.80
SD	0.025	2.701	6.8473	-	4.7219	148.542

Third test system with 15-generators:

This test case includes 15 thermal generating units with all mentioned practical constraints and non-linear characteristics of ELD problem. The total power demand on the system is 2630 MW. The ramp rate limit, POZ and transmission losses are considered in this test and the data is presented in table-VII. The B-loss coefficients are listed in [40]. Unit 2, 5, 6 and 12 are embedded with prohibited operating zones while other have simple operating zone.

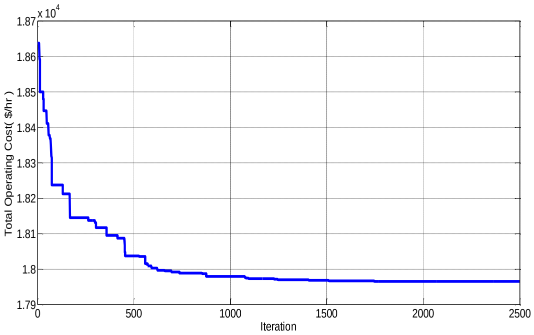

Figure:5.Convergence characteristics of BSA for 13 unit system with valve point loading effect.

The superiority of this algorithm is evident from its ability to satisfy all constraints and provide feasible results. The optimum sharing of loads among generators, transmission losses and generation cost obtained from BSA are compared with otherSSA[27],KGMO [25], IDE[16], DE[16], CCPSO[41], FA[11]and KHA [13]algorithm as presented in table-VIII. Figure-6 shows the convergence of generation costs with iterations of BSA for 15 unit system. It can be seen that rapid convergence in very less number of iterations is obtained by the BSA.

Table-VIII Data of EDP For 15-Unit Test System With Valve Point Loading Effect.

Unit (i)	P_i^{min}	P_i^{max}	a_i	b_i	c_i	UR_i	DR_i	P_i^0	POZs
1	150	455	671	10.1	0.000299	80	120	400	
2	150	455	574	10.2	0.000183	80	120	300	[185,225][305,335][420,450]
3	20	130	374	8.8	0.001126	130	130	105	
4	20	130	374	8.8	0.001126	130	130	100	
5	150	470	461	10.4	0.000205	80	120	90	[180,200][305,335][390,420]
6	135	460	630	10.1	0.000301	80	120	400	[230,255][365,395][430,455]
7	135	465	548	9.8	0.000364	80	120	350	
8	60	300	227	11.2	0.000338	65	100	95	
9	25	162	173	11.2	0.000807	60	100	105	
10	25	160	175	10.7	0.001203	60	100	110	
11	20	80	186	10.2	0.003586	80	80	60	
12	20	80	230	9.9	0.005513	80	80	40	[30,40][55,65]
13	25	85	225	13.1	0.000371	80	80	30	
14	15	55	309	12.1	0.001929	55	55	20	
15	15	55	323	12.4	0.004447	55	55	20	

Table-IX Best solutions and comparison of statistical results of various methods for test case-3 with a demand of 2630 MW.
Table-X

Unit/ power output	**BSA**	**SSA[27]**	**KGMO[25]**	**IDE [16]**	**DE[16]**	**CCPSO[41]**	**FA[11]**	**KHA[13]**
1	455.0000	455.00	454.9835	455.0000	454.7713	455.0000	455.0000	455.0000
2	455.0000	380.00	454.9998	454.9716	455.0000	380.0000	380.0000	455.0000
3	130.0000	130.00	130.0000	129.9991	129.9579	130.0000	130.0000	130.0000
4	130.0000	130.00	130.0000	129.9975	129.7176	130.0000	130.0000	130.0000
5	231.6294	169.9721	235.7674	238.3472	241.0738	170.0000	170.0000	233.8017
6	460.0000	460.00	460.0000	460.0000	460.0000	460.0000	460.0000	460.0000

7	465.0000	430.00	464.9957	465.0000	464.8900	430.0000	430.0000	465.0000
8	60.0001	125.6909	60.0000	60.0208	60.0000	71.7526	71.7450	60.0000
9	25.0000	32.5629	25.0000	25.0068	25.0000	58.9090	58.9164	25.0000
10	35.5955	128.1047	28.0022	26.8588	31.2716	160.0000	160.0000	31.2698
11	74.5425	80.00000	78.1456	76.7466	73.0552	80.0000	80.0000	76.7013
12	79.9990	80.00000	80.0000	80.0000	77.2750	80.0000	80.0000	80.0000
13	25.0000	25.0000	25.0000	25.0039	25.0000	25.0000	25.0000	25.0000
14	15.0000	15.0000	15.0018	15.0000	15.0336	15.0000	15.0000	15.0000
15	15.0000	15.0000	15.0023	15.0098	15.0037	15.0000	15.0000	15.0000
Total power output	2656.767	2656.3306	2656.898	2656.9620	2657.0496	2660.6616	2660.6614	2656.773
P_{Demand}	2630	2630	2630	2630	2630	2630	2630	2630
Ploss	**26.7665**	26.3306	26.8983	26.9620	27.0496	30.6616	30.6614	26.7673
Min. Cost ($/hr)	**32,548.0035**	32,662.51	32,548.1736	32,548.22	32549.2546	32,704.4514	32,704.4501	32,547.3700
Mean cost ($/hr)	32,559.5485	-	32,548.2163	32548.35	32550.4002	32,704.4514	32,8561.10	32,548.1348
Max. cost ($/hr)	32,584.3159	-	32,548.3755	32548.44	32552.0538	32,704.4514	33,175.00	32,548.9326
SD	16.2713	NA	NA	NA	NA	0000	147.1702	NA

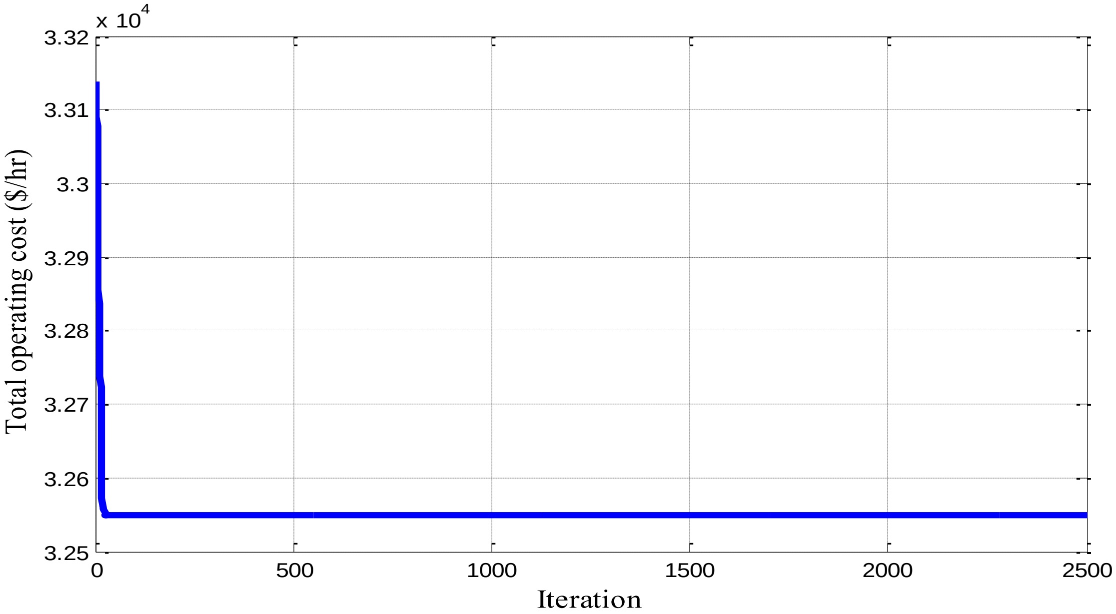

Figure:6. Convergence Characteristics Of BSA For 15 Unit System With POZ And Ramp Rate Limit.

Forth test system with 40-generators:

This test system consists of 40 generating units with valve point loading effect. The required load demand to be met by all 40 generating unit is 10,500 MW. No losses are considered in the system. The system coefficients for this test case are reported in table-X.The superiority of this algorithm is evident from its ability to satisfy all constraints and provide feasible results. The optimum sharing of loads among generators obtained from BSA are compared with other GRASP [28], CBA [14], SSA[27], MFPA [22] and CCPSO[41]algorithm as presented in table-XI. Convergence characteristic of generation cost for 40 unit system is reported in figure-7.

Table-XI Data of EDP For 40-Unit Test System With Valve Point Loading Effect.

Unit (i)	P_i^{min}	P_i^{max}	a_i	b_i	c_i	e_i	f_i
1	36	114	94.705	6.73	0.00690	100	0.084
2	36	114	94.705	6.73	0.00690	100	0.084
3	60	120	309.54	7.07	0.02028	100	0.084
4	80	190	369.03	8.18	0.00942	150	0.063
5	47	97	148.89	5.35	0.01142	120	0.077
6	68	140	222.33	8.05	0.01142	100	0.084
7	110	300	278.71	8.03	0.00357	200	0.042
8	135	300	391.98	6.99	0.00492	200	0.042
9	135	300	455.76	6.60	0.00573	200	0.042
10	130	300	722.82	12.90	0.00605	200	0.042
11	94	375	635.20	12.90	0.00515	200	0.042
12	94	375	654.69	12.80	0.00569	200	0.042
13	125	500	913.40	12.50	0.00421	300	0.035
14	125	500	1760.4	8.84	0.00752	300	0.035
15	125	500	1728.3	9.15	0.00708	300	0.035
16	125	500	1728.3	9.15	0.00708	300	0.035
17	220	500	647.85	7.97	0.00313	300	0.035
18	220	500	649.69	7.95	0.00313	300	0.035
19	242	550	647.83	7.97	0.00313	300	0.035
20	242	550	647.81	7.97	0.00313	300	0.035
21	254	550	785.96	6.63	0.00298	300	0.035
22	254	550	785.96	6.63	0.00298	300	0.035
23	254	550	794.53	6.66	0.00284	300	0.035
24	254	550	794.53	6.66	0.00284	300	0.035
25	254	550	801.32	7.10	0.00277	300	0.035
26	254	550	801.32	7.10	0.00277	300	0.035
27	10	150	1055.1	3.33	0.52124	120	0.077
28	10	150	1055.1	3.33	0.52124	120	0.077
29	10	150	1055.1	3.33	0.52124	120	0.077
30	47	97	148.89	5.35	0.01140	120	0.077
31	60	190	222.92	6.43	0.00160	150	0.063
32	60	190	222.92	6.43	0.00160	150	0.063
33	60	190	222.92	6.43	0.00160	150	0.063
34	90	200	107.87	8.95	0.00010	200	0.042
35	90	200	116.58	8.62	0.00010	200	0.042
36	90	200	116.58	8.62	0.00010	200	0.042
37	25	110	307.45	5.88	0.01610	80	0.098
38	25	110	307.45	5.88	0.01610	80	0.098
39	25	110	307.45	5.88	0.01610	80	0.098
40	242	550	647.83	7.97	0.00313	300	0.035

Table-XII Best Solutions And Comparison Of Statistical Results Of Various Methods For The Test Case-4 With A Demand Of 10500 MW**.**

Unit/ power output	**BSA**	**GRASP[28]**	**CBA[14]**	**SSA[27]**	**MFPA[22]**	**CCPSO[41]**
1	110.7999	110.8003	110.8000	110.8000	110.7998	110.7998
2	110.7999	110.8010	110.8000	110.8000	110.7998	110.7999
3	97.3999	97.3999	97.3999	97.5000	97.3999	97.3999
4	179.7331	179.7331	179.7331	179.6999	179.7331	179.7331
5	87.7999	92.7543	87.7999	87.7999	87.7999	87.7999
6	140.0000	139.9999	140.0000	140.0000	140.0000	140.0000

7	259.5996	259.5996	259.5997	259.5997	259.5996	259.5997
8	284.5996	284.5996	284.5997	284.5998	284.5996	284.5997
9	284.5997	284.5998	284.5997	284.5995	284.5996	284.5997
10	130.0000	130.0000	130.0000	130.0000	130.0000	130.0000
11	94.0000	168.7998	94.0000	94.0000	94	94.0000
12	94.0000	168.7998	94.0000	94.0000	94	94.0000
13	214.7598	214.7598	214.7598	214.7597	214.7597	214.7598
14	394.2794	394.2793	394.2793	394.2793	394.2793	394.2794
15	394.2794	394.2793	394.2794	394.2793	394.2793	394.2794
16	394.2794	304.5195	394.2794	394.2793	394.2793	394.2794
17	489.2794	489.2794	489.2795	489.2793	489.2793	489.2794
18	489.2794	489.2794	489.2794	489.2793	489.2793	489.2794
19	511.2794	511.2794	511.2794	511.2793	511.2793	511.2794
20	511.2794	511.2794	511.2793	511.2793	511.2793	511.2794
21	523.2794	523.2793	523.2794	523.2793	523.2793	523.2794
22	523.2794	523.2793	523.2794	523.2793	523.2793	523.2794
23	523.2794	523.2793	523.2795	523.2793	523.2793	523.2794
24	523.2794	523.2793	523.2794	523.2793	523.2793	523.2794
25	523.2794	523.2793	523.2794	523.2793	523.2793	523.2794
26	523.2794	523.2793	523.2794	523.2793	523.2793	523.2794
27	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000
28	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000
29	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000
30	87.7999	87.8006	87.7999	87.8000	87.7999	87.8000
31	190.0000	189.9999	190.0000	190.0000	190.0000	190.0000
32	190.0000	189.9999	190.0000	190.0000	190.0000	190.0000
33	190.0000	189.9999	190.0000	190.0000	190.0000	190.0000
34	164.7999	164.7999	164.7998	164.6839	164.7998	164.7998
35	200.0000	164.8005	194.3971	194.4408	199.9999	194.3976
36	194.3973	164.8002	200.0000	200.0000	194.3977	200.0000
37	110.0000	109.9999	110.0000	110.0000	109.9999	110.0000
38	110.0000	109.9999	110.0000	110.0000	110.0000	110.0000
39	110.0000	109.9999	109.9999	110.0000	109.9999	93.0962
40	511.2794	511.2794	511.2793	511.2846	511.2793	511.2996
Total power output	10500	10500	10500	10500	10500	10483.12
P_{Demand}	10500	10500	10500	10500	10500	10500
Ploss	0000	0000	0000	0000	0000	0000
Min. Cost ($/hr)	121,412.5391	121,412.55	121,412.5468	121,414.621	121,412.5356	121,403.5362
Mean cost ($/hr)	121,412.5433	NA	121,418.9826	121,736.025	121,425.8516	121,445.3269
Max. cost ($/hr)	121,412.5557	NA	121,436.15	122,245.696	121,465.6338	NA
SD	0.0063	NA	1.611	166.896	22.9908	NA

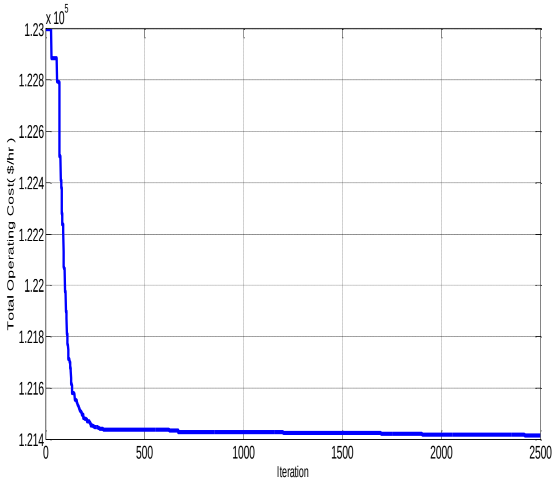

Figure. 7 Convergence Characteristics Of 40 Unit System With Valve Point Loading Effect**.**

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