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Comparative analysis of optimal load dispatch through evolutionary algorithms

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Abstract This paper presents an evolutionary algorithm named as Cuckoo Search algorithm applied to non-convex economic load dispatch problems. Economic load dispatch (ELD) is very essential for allocating optimally generated power to the committed generators in the system by satisfying all of the constraints. Various evolutionary techniques like Genetic Algorithm (GA), Evolutionary programming, Particle Swarm Optimization (PSO) and Cuckoo Search algorithm are considered to solve dispatch problems. To verify the robustness of the proposed Cuckoo Search based algorithm, constraints like valve point loading, ramp rate limits, prohibited operating zones, multiple fuel options, generation limits and losses are also incorporated in the system. In the Cuckoo Search algorithm, the levy flights and the behavior of alien egg discovery is used to search the optimal solution. In comparison with the solution quality and execution time obtained by five test systems, the proposed algorithm seems to be a promising technique to solve realistic dispatch problems.

1. Introduction

In this advancing age economic load dispatch (ELD) problem is one of the major issues in power system operation. With the fuel demand proliferation, there is a need to obtain an optimized solution with reduced generating cost of different generating units in a power system. Using various mathematical programming methods and optimization techniques, the problems are solved. The conventional methods include lambda-iteration method, base point methods which are clearly mentioned in [1,2]. All these mentioned methods compute the optimal solutions by taking the incremental cost curves as a linear function of generating units. But practically, a highly non-linear cost curves cannot be solved by the above method and for this reason the final optimized solution is slightly far from the actual result. This can be neglected for generating units of power system for a small period of time, but focusing on a long term basis, its negligence causes a huge loss.

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Nomenclature

P_D	load demand
P_i	real power output of ith generating unit
a_i, b_i and c_i	fuel cost coefficients of ith generating unit
e_i, f_i	coefficients of the ith unit with valve point effects
m	number of committed online generators
P_{Loss}	transmission loss
B_{ij}, B_{0i}, B_{00}	B-matrix coefficients for transmission power loss
$P_{i\min}$	minimum real power output of ith generator
$P_{i\max}$	maximum real power output of ith generator
P_i^0	previous real power output of ith generator
U_{ri}	up ramp limits of the ith generator
D_{ri}	down ramp limits of the ith generator
P_{iL}^{pzk}	lower limits of kth prohibited zone for ith generating unit
P_{iU}^{pzk}	upper limits of kth prohibited zone for ith generating unit
$Iter$	maximum number of iterations
It	current iteration number

The nonlinear characteristics of certain generating units include different factors like discontinuous prohibited zones, ramp rate limits, multiple fuel options, start-up cost functions and valve point loadings [3] which are in general non-smooth. While taking the large power system into consideration due to oscillatory problem in load change, conventional method is quite unreliable and takes huge time for computation. In order to solve the ELD problem, dynamic programming (DP) method is properly studied in [4]. But the main disadvantage of this method is that when applied to higher number of units of power system requires enormous computational efforts.

During the last decade, various computational algorithms such as Genetic Algorithms (GA) [5–9], Evolutionary programming [10], Artificial neural networks (ANNs) [11–14], Particle Swarm Optimization (PSO) [15–20] are applied to obtain an optimized solution. To make these numerical methods more convenient and simpler toward solving of ELD problem, intelligent algorithms have been applied. Hopfield neural networks have been successfully implemented in [11–14] but this method suffers some huge calculation due to involvement of higher numbers of iterations. Recently GA is found to be deficient in its performance due to its high correlation between the crossover and mutation which give rise to high average fitness toward the end of the evolutions. PSO is very much concerned about the higher number of iterations which result higher execution time. Various swarm intelligence based algorithms such as Ant colony optimization ACO [21], Artificial bee colony algorithm (ABC) [22], Hybrid Harmony search algorithm (HHS) [23] and Fuzzy based chaotic ant colony optimization (FCACO) [24] algorithms have been successfully applied to economic load dispatch problems.

Cuckoo search based optimization is found to be one of the most sophisticated, less time consuming evolutionary algorithms in order to solve the nonlinear economic load dispatch problems. Though Cuckoo search highly depends upon the tolerance value but its converging logic is really commendable [25–29]. In this paper, 6, 15, 40, 140 and 320 units system are taken into consideration. For more realistic analysis the loss coefficients are included in few cases in the system under consideration. Different costs of various generating units under study are calculated by three evolutionary techniques named Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Cuckoo Search algorithm and the results are compared by both numerically and graphically by taking the minimum operating cost as objective function.

2. Problem formulation

2.1. Economic dispatch

The ELD problem is a nonlinear programming optimization task and its aim is to minimize the fuel cost of generating real power outputs for a specified period of operation so as to accomplish optimal dispatch among the committed units and satisfying all the system constraints. Here, two models for ELD are considered, viz. one with smooth cost functions of the generators and the other with non-smooth cost functions with valve point loading effects as detailed below.

2.2. ELD problem with smooth cost functions

The main objective of the ELD problem is to determine the most economic loadings of generators to minimize the generation cost such that the load demands P_D in the intervals of the generation scheduling horizon can be met and simultaneously the practical operation constraints like system load demand, generator output limits, system losses, ramp rate limits and prohibited operating zones are to be satisfied.

Here, the constrained optimization problem is formulated as

$$\text{Minimize} \quad F = \sum_{i=1}^{m} f_i(P_i) \tag{1}$$

F is the total cost function of the system.

In general, the cost function of ith unit $f_i(P_i)$ is a quadratic polynomial expressed as

$$f_i(P_i) = a_i + b_i P_i + c_i P_i^2 \quad (\$/h) \tag{2}$$

This minimization problem is subjected to a variety of constraints depending upon assumptions and practical implications like power balance constraints, generator output limits, ramp rate limits and prohibited operating zones. These constraints and limits are discussed as follows.

(a) Power balance constraint or demand constraint: The total generation $\sum_{i=1}^{m}(P_i)$ should be equal to the total system demand P_D plus the transmission loss P_{Loss} that is represented as

$$\sum_{i=1}^{m}(P_i) = P_D + P_{Loss} \tag{3}$$

Due to geographical distribution of the power plant, the transmission line losses must be taken into account to get the more realistic solution. As the transmission loss is a function of generation and its value is calculated by cost coefficient method as described in [10]. It can be expressed as a quadratic function, as shown in the following

$$P_{Loss} = \sum_{i=1}^{m}\sum_{j=1}^{m} P_i B_{ij} P_j + \sum_{i=1}^{m} B_{0i} P_i + B_{00} \quad (4)$$

(b) The generator limits: The generation output of each unit should be between its minimum and maximum limits. That is, the following inequality constraint for each generator should be satisfied.

$$P_{i\min} \leqslant P_i \leqslant P_{i\max} \quad (5)$$

(c) Ramp rate limits: In ELD problems, the generator output is usually assumed to be adjusted smoothly and instantaneously. However, under practical circumstances ramp rate limit restricts the operating range of all the online units for adjusting the generation operation between two operating periods. The inequality constraint due to the ramp rate limits [15] of ith unit due to the change in generation is given by the following constraint.

$$Max\left(P_{i\min}, P_i^0 - D_{ri}\right) \leqslant P_i \leqslant Min(P_{i\max}, P_i^0 + U_{ri}) \quad (6)$$

if generation increases,

$$P_i - P_i^0 \leqslant U_{ri} \quad (7)$$

if generation decreases,

$$P_i^0 - P_i \leqslant D_{ri} \quad (8)$$

(d) Prohibited operating zones: the input–output characteristics of modern units are inherently nonlinear because of the steam valve point loadings [3,5]. The operating zones due to valve point loading or vibration due to shaft bearing are generally avoided in order to achieve best economy, called prohibited operating zones of a unit, which make the cost curve discontinuous in nature. The feasible operating zones of ith unit having k number of prohibited operating zones are represented by

$$P_i \notin [P_{iL}^{pzk}, P_{iU}^{pzk}] \; k = 1, 2, \ldots \quad (9)$$

$$P_i \leqslant P_{iL}^{pzk} \text{ and } P_i \geqslant P_{iU}^{pzk} \quad (10)$$

2.3. Cost functions with valve-point effects

The generators with multiple valve steam turbines possess a wide variation in the input–output characteristics [5]. The valve point effect introduces ripples in the heat rate curves and cannot be represented by the polynomial function as in (2). Therefore, the actual cost curve is a combination of sinusoidal function and quadratic function represented by the following equation.

$$f_i(P_i) = a_i + b_i P_i + c_i P_i^2 + |e_i \times \sin(f_i \times (P_{i\min} - P_i))| \quad (11)$$

2.4. Cost function with valve point effects and change of fuels

According to the valve point loadings and multiple fuel options in the objective function of the practical economic dispatch problem has non-differentiable points in reality. Therefore, the objective function should be composed of quadratic and sinusoidal function i.e., a set of non-smooth functions to obtain an accurate and true economic dispatch solution. The cost function is framed by combining both valve point loadings and multi-fuel options which can be realistically represented as shown below in (12).

$$F_i(P_i) = \begin{cases} a_{i1} + b_{i1} P_i + c_{i1} P_i^2 + |e_{i1} \times \sin(f_{i1} \times (P_{i1\min} - P_{i1}))| & ,for.fuel1, \quad P_{i1\min} \leqslant P_i \leqslant P_{i1} \\ a_{i2} + b_{i2} P_i + c_{i2} P_i^2 + |e_{i2} \times \sin(f_{i2} \times (P_{i2\min} - P_{i2}))| & ,for.fuel2, \quad P_{i2\min} \leqslant P_i \leqslant P_{i2} \\ \vdots & \vdots \quad \vdots \\ a_{im} + b_{im} P_i + c_{im} P_i^2 + |e_{im} \times \sin(f_{im} \times (P_{im\min} - P_{im}))| & ,for.fuel.m, \quad P_{im\min} \leqslant P_i \leqslant P_{im} \end{cases} \quad (12)$$

3. Evolutionary algorithms

3.1. Cuckoo search optimization

Cuckoo Search is an evolutionary population-based optimization method [25–29]. It is an evolutionary search which relies on natural process of birds flocking for food randomly. It is based on the obligate brood parasitic behavior of some cuckoo species in combination with levy flights of some birds and fruit flies. It solely enhances the behavior of laying eggs and breeding of cuckoos. They exist naturally in two forms: matured cuckoos and eggs. Every cuckoo tries to place its egg in other nests in order of not being detected by the parent cuckoo, where it all depends on the resemblance of the alien egg and the host egg. In this step, the alien eggs are detected and being thrown out of the nest. Naturally the cuckoos often make mistakes as the eggs resemble quite high. So, there is a probability involved in detecting the alien eggs which is used as a parameter for the optimization algorithm. After this process, the eggs hatch and the cuckoos mature. They tend to find a globally optimal solution or habitat. Breeding for food has always been a quasi-random process since, they are not aware of the geographical location of the best habitat. The birds tend to converge toward the best habitat acquired by a bird in the best position. In this way, the whole population reaches the habitat. This best environment becomes their new place for breeding and reproduction. Further, breeding for food is one of the features included in *Levý flights* [25].

3.2. Importance of the proposed Cuckoo Search algorithm

The proposed Cuckoo Search algorithm efficiently and effectively handles the real world complex dispatch problems. In

CSA method the two main features are combined together to constitute a powerful search ability to find out the optimal solution. In the search process, levy flights are used to guide the search direction and the behavior of alien egg discovery in a nest of a host bird is used to obtain the global solution. In order to avoid local solution, α' the step size of levy flights is varied with the equation $\alpha' = \alpha\sqrt{It}$ because the diversity of population descends faster during the solution process. The variation of alpha maintains the diversity of population and ensuring a high probability of obtaining the global optimum. The other important feature of CSA method is that the behavior of alien egg discovery in a nest with a probability Pa introduces perturbation in the search process, which maintains inherent randomness in solution quality.

The computational procedures in steps are described below. Steps:

1. Initialize the population size N as number of sets for the number of units and probability of alien egg discovery P_a.
2. Initialize the minimum and maximum bound L_b and U_b as the minimum and maximum values of generation for every unit respectively.
3. The population is initialized using the random function. Each nest is a feasible potential solution of the defined problem.

$$nest(i,j) = L_b + (U_b - L_b) * rand \times (size(L_b)) \tag{13}$$

4. Calculate the fitness function according to the number of Cuckoos. Run the loop for the condition such that the new fitness value is just below the fitness value of the optimal trial values. The best fitness nest in population is considered as *Xbest_nest*. The best nest in all evaluations is considered as *Gbest_nest*.
5. Determine the sigma value using gamma and beta distribution factors, the value of beta varies from 0.2 to 1.99.

$$\sigma_u = \left\{ \frac{\gamma(1+\beta)\sin(\frac{\pi\beta}{2})}{\gamma[(1+\beta)/2]\beta^{*}2^{\frac{(\beta-1)}{2}}} \right\}^{\frac{1}{\beta}} \tag{14}$$

6. Find new nest using new step size α' by the following equations.

$$newnest = Xbest\_nest + \alpha' \times Nest\_discovery \tag{15}$$

Where, $\alpha' = \frac{\alpha}{\sqrt{It}}$, $Nest\_discovery$
$= \sigma_u(Xbest\_nest - Gbest\_nest)$

7. Check if, *new fitness value* < *fitness value*. If yes, update it to the fitness value. Also, update the corresponding nest values to the *newnest*. If no, the fitness value retains its previous value. The fitness function here comprises of the cost function and the objective is minimized here. A penalty factor has been added in the end to satisfy the various constraints used in the load dispatch problem.
8. Check for new solution using random value > P_a to obtain a new step size *new_stepsize* and thus obtain *newnest* by Eq. (15). If the stopping criterion of maximum number of iterations is not reached then, go to the Step 4. Otherwise, print the optimal solution.

4. Simulation and results

The present work has been implemented in Matlab-7.10.0.499 (R2010a) environment on a 3.06 GHz, Pentium-IV; with 1 GB RAM PC for the solution of economic load dispatch problem of five standard systems. The systems under study have been considered one by one and the evolutionary programs have been written (in .m file) to calculate the solution of economic load dispatch problems and its results are compared with each other for first three systems and for last two systems only CSA method is implemented for the solutions. The evolutionary algorithms such as are genetic algorithm, particle swarm optimization and proposed CSA technique have been successfully applied to dispatch problems by considering all equality and inequality constraints.

Implementation of CSA requires the determination of some fundamental issues like: number of nests, eggs, number of iteration, initialization, termination and fitness value, step size, levy flights and an alien egg with a probability $p_a \in [0, 1]$. The success of CSA algorithm is also heavily dependent on setting of control parameters namely population size (nests), step size, maximum generation and probability of alien eggs. While applying CSA, its control parameters should be carefully chosen for the successful implementation of the algorithm. A series of experiments were conducted to select the control parameters of the proposed CSA method. To quantify the results, 25 independent runs were executed for each parameter variation. The best setting of control parameter is alien egg probability $P_a = 0.20$, distribution factor $\beta = 1.8$, number of nests $N = 50$, number of iterations $Iter = 500$, which are also shown in Table 1.

The details of GA parameters used are population, $pop = 50$, Crossover probability, $pcross = 0.5$, Mutation probability, $pmute = 0.01$. The details of PSO, are described in [15–20] and the parameters used are population, $N = 20$, $w_{max} = 0.9$, $w_{min} = 0.4$, $c_1 = c_2 = 2$.

4.1. Six unit system

In this system, the B-coefficient matrix or loss coefficient matrix is adopted from [20], the cost coefficients and output limits of each generator are depicted in Table 2. For comparison point of view, the load demand is varied from 750 MW to 1050 MW with an increment of 100 MW at a time. The evolutionary algorithms i.e., GA, PSO and proposed CSA have been applied to this system by considering different load demands such as, P_D = 750 MW, 850 MW, 950 MW and 1050 MW respectively. The convergence characteristics of the three considered evolutionary algorithms are shown in Figs. 1–4 for different load demands. Among the three evolutionary algorithms, the CSA provides the cheapest generation schedule for various load demands. The execution time is also smaller in case of proposed CSA technique, which is shown in Table 3 and Figs. 1–4. The bar charts of the three evolutionary algorithms are shown in Fig. 5 representing the total generation cost for various load demands. Consequently, the proposed CSA technique provides better results in terms of minimum cost and convergence time for different load demands for this six unit system.

Table 1 Control parameters' tuning for Cuckoo Search algorithm.

Parameters	Value	Minimum value	Average value	Maximum value	Standard deviation	Other parameters
β	1.1	39,348	39461.7	39,660	115.65	$N = 50,\ iter = 500,$ $P_a = 0.25$
	1.2	39,315	39526.7	39,824	176.41	
	1.3	39,318	39430.4	39,552	79.94	
	1.4	39,324	39543.0	39,597	113.00	
	1.5	39,340	39409.6	39,673	102.89	
	1.6	39,357	39488.7	39,599	85.19	
	1.7	39,342	39419.9	39,544	91.53	
	1.8	**39,308**	39401.1	39,653	126.84	
	1.9	39,310	39434.0	39,543	83.14	
	2.0	39,331	39486.8	39,612	91.59	
P_a	0.05	39,322	39384.1	39,525	125.20	$N = 50,\ iter = 500,$ $\beta = 0.8$
	0.10	39,314	39382.6	39,672	115.68	
	0.15	39,292	39372.6	39,655	79.94	
	0.20	**39,287**	39393.3	39,571	105.91	
	0.25	39,294	39377.7	39,578	116.56	
	0.30	39,298	39435.5	39,605	94.75	
	0.35	39,305	39452.9	39,627	102.16	
	0.40	39,309	39443.4	39,547	96.19	
	0.45	39,315	39540.0	39,704	168.93	
	0.50	39,335	39476.0	39,617	85.10	

Bold fonts indicate minimum function value.

Table 2 Six unit data.

Unit	a_i	b_i	c_i	$P_{\min}$	$P_{\max}$
1	756.79886	38.53	0.15240	10	125
2	451.32513	46.15916	0.10587	10	150
3	1049.9977	40.39655	0.02803	35	225
4	1242.5311	38.30443	0.03546	35	210
5	1658.5696	36.32782	0.02111	130	325
6	1356.6592	28.27041	0.01799	125	315

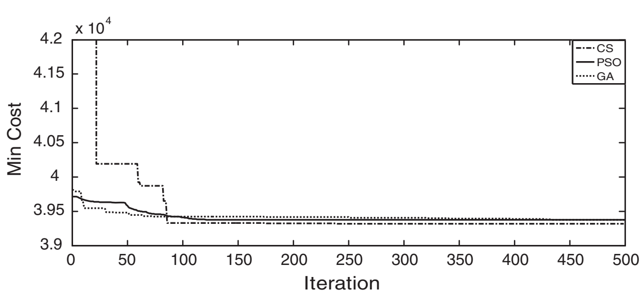

Figure 1 Convergence characteristics of evolutionary algorithms for 6 unit system with load demand $P_{\mathrm{LOAD}} = 750$ MW.

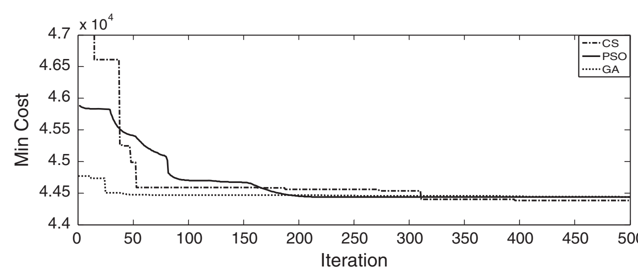

Figure 2 Convergence characteristics of evolutionary algorithms for 6 unit system with load demand $P_{\mathrm{LOAD}} = 850$ MW.

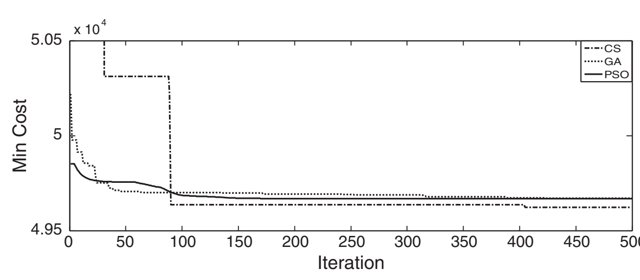

Figure 3 Convergence characteristics of evolutionary algorithms for 6 unit system with load demand = 950 MW.

4.2. Fifteen unit system

4.2.1. Without ramp rate constraints and prohibited operating zones

This system contains 15 thermal generating units; the B-coefficient matrix is adopted from [15] and the cost coefficients as well as the minimum and maximum limits of each generator output have been shown in Table 4. For comparative analysis point of view, the load demand is varied from 2430 MW to 2730 MW with an increment of 100 MW at a time. The evolutionary algorithms i.e., GA, PSO and proposed CSA have been applied to this system by considering different load demands such as, P_D = 2430 MW, 2530 MW, 2630 MW and 2730 MW respectively. The results of evolutionary algorithms are compared with each other and also reported in Table 5. The convergence characteristics of the three evolutionary algorithms for fifteen unit system for different load demands are shown in Fig. 6–9. It is found from Table 5 that there is no sig-

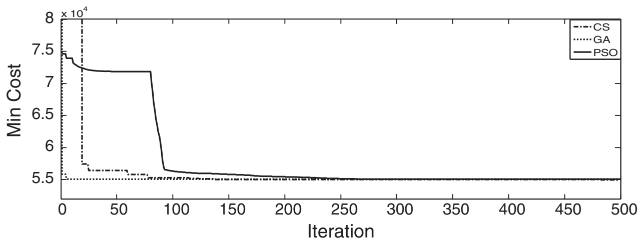

Figure 4 Convergence characteristics of evolutionary algorithms for 6 unit system with load demand P_{LOAD} = 1050 MW.

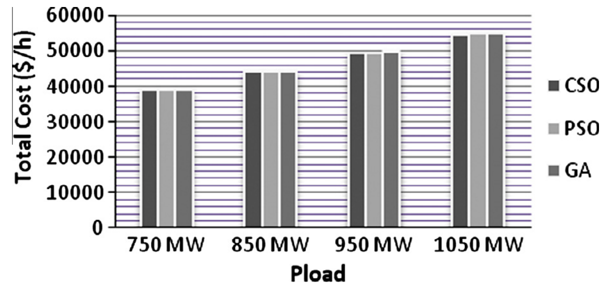

Figure 5 Comparison chart for 6 unit system for different load demands.

nificant reduction of execution time as load demand increases. The execution time increases as the number of units in the system increases irrespective to the type of algorithm used. However, the optimal cost and its execution time requirement to provide the optimal results in case of proposed CSA method are better as compared to that of PSO and GA technique which are seen from Figs. 6–9 and also from Table 5. In this system, after applying the various evolutionary algorithms, the best cost value out of 20 trials is taken as the optimal cost of the system. The optimal cost obtained is considered as the cheapest generation schedule of power system has been reported in Table 5.

4.2.2. With ramp rate constraints and prohibited operating zones

This system consists of 15-unit system. To verify the robustness of the proposed approach in solving non-smooth functions exhibiting prohibited operating zones, transmission losses and ramp rate constraints, are being considered in the cost function. In this case the load demand is considered as 2630 MW and its input data are adopted from [15].

The optimal solutions obtained by the proposed CSA method along with other methods such as IPSO [20], ABC [22] and HHS [23] are provided in Table 6. The global optimum solution for 15-generators system is yet to be discovered. It was reported that, the optimal solution for 15 generator system was 32706.6580 $/h by the IPSO method [20]. The ABC and HHS methods fail to satisfy the power balance equation i.e., the load demand is not exactly 2630 MW. The optimal solution among 25 trials by the proposed CSA method is found as 32706.6582 $/h, the loss 30.85773 MW, average computational time 2.226 s with the standard deviation 18.792 by satisfying all the constraints, such as power balance, ramp rate limits, prohibited operating zones, generation limits and transmission loss thereby validating the stochastic applicability. Moreover, it is evident from this table that there is a power mismatch in other two methods except the proposed CSA and IPSO [20] methods providing very similar results. The

Table 4 15-Unit data.

Unit	a_i	b_i	c_i	P_{min}	P_{max}
1	0.000299	10.1	671	150	455
2	0.000183	10.2	574	150	455
3	0.001126	8.80	374	20	130
4	0.001126	8.80	374	20	130
5	0.000205	10.4	461	150	470
6	0.000301	10.1	630	135	460
7	0.000364	9.80	548	135	465
8	0.000338	11.2	227	60	300
9	0.000807	11.2	173	25	162
10	0.001203	10.7	175	25	160
11	0.003586	10.2	186	20	80
12	0.005513	9.90	230	20	80
13	0.000371	13.1	225	25	85
14	0.001929	12.1	309	15	55
15	0.004447	12.4	323	15	55

Table 3 Total generation cost and corresponding generation levels, transmission loss and execution time for 6 unit system for various load demands.

Load demand	P_{LOAD} = 750 MW			P_{LOAD} = 850 MW			P_{LOAD} = 950 MW			P_{LOAD} = 1050 MW		
Outputs	CSO	PSO	GA	CSO	PSO	GA	CSO	PSO	GA	CSO	PSO	GA
P_1 (MW)	46.55	30.42	31.25	26.82	34.65	34.48	41.35	38.93	39.08	52.66	43.50	43.81
P_2 (MW)	20.64	10.92	11.31	23.12	17.41	17.93	48.68	24.00	23.47	54.84	31.07	30.96
P_3 (MW)	155.23	130.12	129.16	189.00	152.33	151.71	147.43	174.78	173.85	198.03	198.69	197.66
P_4 (MW)	88.09	127.25	126.87	148.79	144.31	145.28	188.83	161.53	162.69	185.84	179.91	180.46
P_5 (MW)	226.82	244.01	244.96	212.00	270.36	271.26	291.52	296.85	297.39	320.26	325.00	324.87
P_6 (MW)	234.24	229.42	228.67	277.89	259.31	258.83	266.56	285.93	285.19	279.80	315.00	314.72
P_{loss} (MW)	21.35	22.17	22.76	27.79	28.38	28.52	33.16	35.42	35.51	42.83	43.19	43.65
Fuel Cost ($/hr)	39287.70	39376.22	39376.30	44381.59	44440.20	44440.22	49622.15	49669.31	49969.56	54979.73	55067.89	55067.90
Time(s)	0.434	0.556	0.587	0.439	0.559	0.591	0.438	0.558	0.590	0.438	0.560	0.592

Table 5 Total generation cost and corresponding generation levels, transmission loss and execution time for 15 unit system for various load demands.

Load demand MW	2430			2530			2630			2730		
	CSO	PSO	GA	CSO	PSO	GA	CSO	PSO	GA	CSO	PSO	GA
P_1	383.51	443.48	150.00	347.18	455.00	454.03	426.30	455.00	150.92	455.00	455.00	454.13
P_2	454.62	399.67	454.78	414.53	455.00	418.50	400.53	455.00	454.43	363.85	455.00	361.52
P_3	129.58	130.00	126.64	130.00	130.00	96.31	97.77	130.00	130.00	129.87	130.00	128.31
P_4	48.42	130.00	97.74	106.39	130.00	20.79	104.49	130.00	129.12	129.88	130.00	85.39
P_5	383.317	150.00	275.42	233.17	160.28	447.55	242.65	236.47	469.12	381.29	314.971	410.66
P_6	135.16	460.00	402.97	294.62	459.98	229.98	324.86	460.00	340.69	282.81	459.97	459.63
P_7	464.25	465.00	274.73	327.64	465.00	461.86	429.54	465.00	364.58	372.18	464.99	465.00
P_8	90.75	60.00	240.38	205.72	60.00	60.00	91.27	60.00	299.21	218.97	60.00	76.50
P_9	32.20	25.00	77.91	161.91	25.00	99.94	158.35	25.00	28.71	117.17	25.00	27.41
P_{10}	25.26	25.00	103.46	158.65	25.00	88.29	101.97	28.50	56.18	47.20	52.71	25.66
P_{11}	72.15	48.31	42.47	31.02	62.04	41.34	59.25	76.99	56.97	78.26	78.26	70.20
P_{12}	79.38	61.00	79.60	30.76	72.06	34.11	79.03	80.00	54.05	48.31	79.99	42.34
P_{13}	51.29	25.00	25.00	36.46	25.00	29.49	49.13	25.00	39.01	28.87	25.00	70.36
P_{14}	42.41	15.00	37.29	25.64	15.00	21.93	20.45	15.00	26.83	50.88	15.00	37.29
P_{15}	37.66	15.00	41.57	26.24	15.00	25.82	44.34	15.00	30.12	25.42	15.00	15.53
P_{loss}	21.68	22.48	24.69	21.47	24.38	26.94	24.71	26.97	29.03	27.84	30.91	32.58
Fuel cost ($/h)	30404.36	30585.92	30762.9	31382.0	31467.9	31650.9	32301.53	32549.2	32892.72	33302.14	33649.46	33772.74
Time (s)	0.56	0.68	0.72	0.56	0.68	0.72	0.56	0.68	0.72	0.56	0.68	0.72

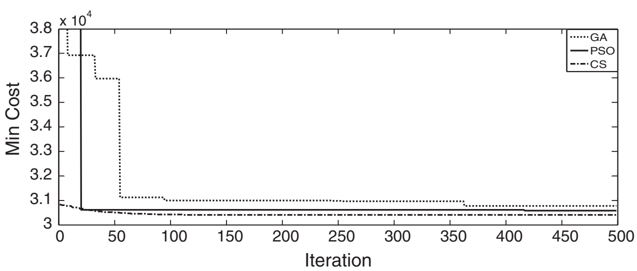

Figure 6 Convergence characteristics of evolutionary algorithms for 15 unit system with P_{LOAD} = 2430 MW.

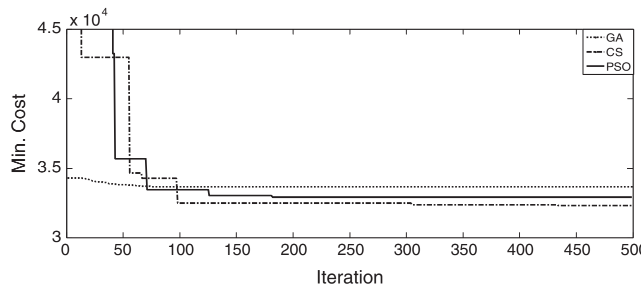

Figure 8 Convergence characteristics of evolutionary algorithms for 15 unit system with P_{LOAD} = 2630 MW.

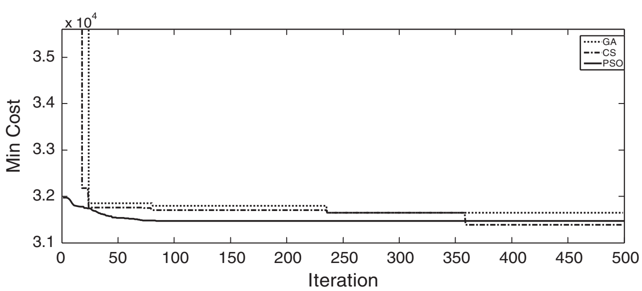

Figure 7 Convergence characteristics of evolutionary algorithms for 15 unit system with P_{LOAD} = 2530 MW.

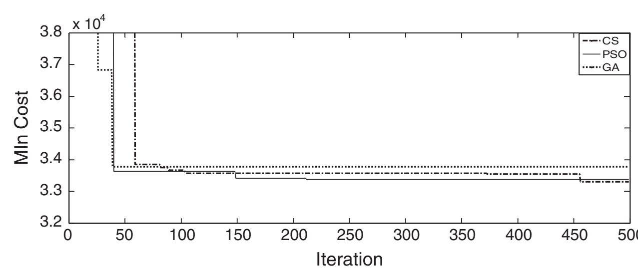

Figure 9 Convergence characteristics of evolutionary algorithms for 15 unit system with P_{LOAD} = 2730 MW.

standard deviation and convergence time of proposed CSA method is better than IPSO method [20]. The convergence characteristic of the proposed CSA technique is shown in Fig. 10. The bar charts of the three evolutionary algorithms are shown in Fig. 11 representing the total generation cost for various load demands. It is clear from the Table 6 and Fig. 11, the Cuckoo Search algorithm outperforms in comparison with PSO and GA techniques.

4.3. Forty unit system

40-Unit system is a large scale 40-unit realistic power system which contains 40 thermal generating units being a mixture of oil-fuelled, coal-fuelled cycle generating units. To show the applicability and efficiency of proposed CSA method, valve point loading effect has been incorporated in the cost function. The input data of forty unit system are shown in Table 7. The

Table 6 Best solution of evolutionary algorithms for 15 unit system with load demand P_{LOAD} = 2630 MW.

Unit power output (MW)	CSO (proposed)	IPSO [20]	ABC [22]	HHS [23]
P_1	455.0000	455.0000	455.0000	455.0000
P_2	380.0000	380.0000	380.0000	379.9954
P_3	130.0000	130.0000	130.0000	130.0000
P_4	130.0000	130.0000	130.0000	130.0000
P_5	170.0000	170.0000	169.9997	169.9572
P_6	460.0000	460.0000	460.0000	460.0000
P_7	429.99993	430.0000	430.0000	430.0000
P_8	71.9524	71.8762	71.9698	81.8563
P_9	58.9072	58.98125	59.1798	47.8546
P_{10}	159.9981	160.0000	159.8004	160.0000
P_{11}	80.0000	80.0000	80.0000	80.0000
P_{12}	80.0000	80.0000	80.0000	79.9959
P_{13}	25.0000	25.0000	25.0024	25.0000
P_{14}	15.0001	15.0000	15.0056	15.0000
P_{15}	15.0000	15.0000	15.0014	15.0000
Total power output	2660.85773	2660.85745	2660.95910	2659.65940
P_{loss} (MW) Reported	30.85773	30.85745	30.86010	29.66314
P_{loss} (MW) tested	30.85773	30.85745	30.86010	30.83945
Load demand (MW)	2630.0000	2630.0000	2630.09900	2628.81995
Total gen. cost ($/h)	32,706.6582	32,706.6580	32,707.8551	32,692.8361

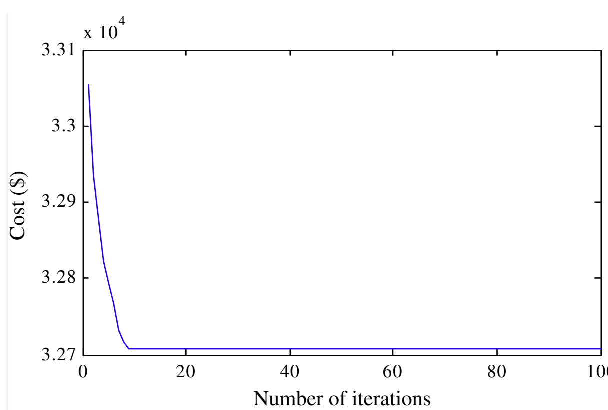

Figure 10 Convergence characteristics of Cuckoo search for 15 unit system.

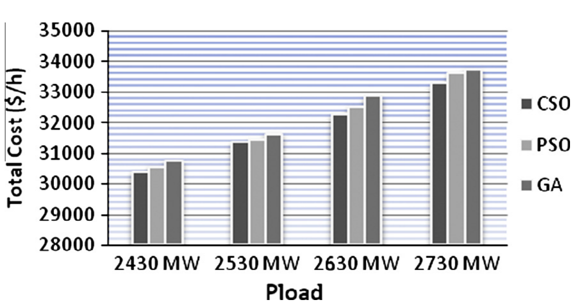

Figure 11 Comparison chart for 15 unit system for different load demands.

Table 7 Forty unit data.

Unit	a_i	b_i	c_i	P_{min}	P_{max}
1	0.03073	8.336	170.44	40	80
2	0.02028	7.0706	309.54	60	120
3	0.00942	8.1817	369.03	80	190
4	0.08482	6.9467	135.48	24	42
5	0.09693	6.5595	135.19	26	42
6	0.01142	8.0543	222.33	68	140
7	0.00357	8.0323	287.71	110	300
8	0.00492	6.999	391.98	135	300
9	0.00573	6.602	455.76	135	300
10	0.00605	12.908	722.82	130	300
11	0.00515	12.986	635.2	94	375
12	0.00569	12.796	654.69	94	375
13	0.00421	12.501	913.4	125	500
14	0.00752	8.8412	1760.4	125	500
15	0.00708	9.1575	1728.3	125	500
16	0.00708	9.1575	1728.3	125	500
17	0.00708	9.1575	1728.3	125	500
18	0.00313	7.9691	647.85	220	500
19	0.00313	7.955	649.69	220	500
20	0.00313	7.9691	647.83	242	550
21	0.00313	7.9691	647.83	242	550
22	0.00298	6.6313	785.96	254	550
23	0.00298	6.6313	785.96	254	550
24	0.00284	6.6611	794.53	254	550
25	0.00284	6.6611	794.53	254	550
26	0.00277	7.1032	801.32	254	550
27	0.00277	7.1032	801.32	254	550
28	0.52124	3.3353	1055.1	10	150
29	0.52124	3.3353	1055.1	10	150
30	0.52124	3.3353	1055.1	10	150
31	0.25098	13.052	1207.8	20	70
32	0.16766	21.887	810.79	20	70
33	0.2635	10.244	1247.7	20	70
34	0.30575	8.3707	1219.2	20	70
35	0.18362	26.258	641.43	18	60
36	0.32563	9.6956	1112.8	18	60
37	0.33722	7.1633	1044.4	20	60
38	0.23915	16.339	832.24	25	60
39	0.23915	16.339	832.24	25	60
40	0.23915	16.339	1035.2	25	60

load demand is varied from 7550 MW to 10550 MW with an increment of 1000 MW at a time. The evolutionary optimization algorithms have been implemented for various load demands without valve point loading effects and the comparative analysis of their results have been reported in Table 8. The proposed CSA technique has been applied to the above power system by addition of valve point loading effect and its results are reported in Table 9. The addition of valve point loading effect in cost function increases the total generation cost of the power system. The convergence characteristics of the three considered evolutionary algorithms are shown in Figs. 12–15 for different load demands. The bar charts of the three evolutionary algorithms are also shown in Fig. 16, representing the total generation cost for various load demands without valve point loading effect in case of forty unit system. Among these three evolutionary algorithms, the CSA provides the cheapest generation schedule for various load demands. The proposed CSA method seems to be better method in comparison with PSO and GA methods.

Table 8 Comparison of generation cost of evolutionary algorithms without valve point loading effect for 40 unit system with P_{LOAD} = 7550 MW, 8550 MW, 9550 MW and 10,550 MW.

Load demand	7550 MW			8550 MW			9550 MW			10,550 MW		
	CSO	PSO	GA	CSO	PSO	GA	CSO	PSO	GA	CSO	PSO	GA
P_1	67.29	46.63	72.34	47.44	63.47	71.60	68.88	54.14	76.06	40.08	56.92	78.15
P_2	115.61	94.41	102.68	118.47	97.86	120.00	115.87	94.99	118.94	120.00	112.68	120.00
P_3	140.51	122.00	156.28	83.71	96.23	190.00	188.88	147.03	189.32	180.19	80.00	190.00
P_4	27.00	25.67	26.74	24.01	39.34	30.16	41.88	41.83	40.55	24.27	36.69	39.28
P_5	33.16	26.14	37.18	36.07	31.98	34.46	28.71	32.04	42.00	36.03	31.27	33.03
P_6	113.85	109.89	124.55	87.35	125.27	138.55	78.09	130.14	135.15	131.17	243.91	138.79
P_7	136.23	294.97	287.92	300.00	222.55	299.59	298.89	298.64	300.00	299.89	300.00	300.00
P_8	138.16	297.86	198.62	193.38	146.41	300.00	297.53	251.89	300.00	291.42	300.00	300.00
P_9	160.78	297.83	138.71	193.81	139.03	300.00	206.61	200.93	300.00	298.73	180.47	300.00
P_{10}	193.10	130.00	223.18	247.28	223.41	130.00	244.57	292.55	206.27	288.97	264.92	259.97
P_{11}	278.63	94.00	106.12	195.51	190.63	94.00	351.26	96.03	144.00	374.99	327.22	339.84
P_{12}	213.48	94.00	246.91	335.11	372.54	94.00	133.79	124.66	178.53	374.99	278.14	350.46
P_{13}	367.15	125.00	248.83	392.75	499.53	129.79	429.71	495.72	275.68	499.99	187.09	500.00
P_{14}	143.45	141.65	152.37	391.50	412.37	229.66	450.50	491.23	379.73	365.29	443.27	487.12
P_{15}	414.63	125.87	328.96	374.81	483.79	245.87	500.00	437.19	348.11	498.49	370.73	500.00
P_{16}	327.30	125.00	263.92	278.13	283.75	248.78	441.31	460.58	411.98	499.94	248.79	467.55
P_{17}	203.49	130.46	178.05	426.01	409.14	252.33	360.05	492.35	464.74	491.71	452.97	497.29
P_{18}	414.49	466.07	379.02	284.74	454.99	500.00	227.08	407.55	500.00	499.21	500.00	500.00
P_{19}	351.82	400.45	403.20	428.14	291.55	500.00	359.62	275.34	498.12	306.04	500.00	499.87
P_{20}	332.37	415.75	318.48	409.38	446.36	550.00	550.00	545.07	550.00	532.94	550.00	550.00
P_{21}	279.41	444.79	356.91	387.36	242.19	550.00	481.74	352.18	550.00	549.92	550.00	550.00
P_{22}	537.67	550.00	498.01	334.75	331.39	550.00	537.70	550.00	550.00	524.05	550.00	550.00
P_{23}	396.66	550.00	550.00	449.68	391.40	550.00	550.00	545.30	550.00	549.93	542.47	550.00
P_{24}	387.95	549.94	308.92	550.00	540.82	550.00	537.00	549.53	550.00	542.77	528.37	550.00
P_{25}	418.23	550.00	479.70	503.98	549.82	550.00	549.72	512.33	550.00	547.96	429.00	550.00
P_{26}	473.03	550.00	343.21	549.99	536.19	550.00	369.72	550.00	545.94	549.44	512.34	550.00
P_{27}	263.63	549.99	533.48	284.82	389.13	550.00	550.00	518.12	550.00	549.85	329.83	546.36
P_{28}	82.88	10.00	15.38	91.43	10.16	10.00	44.43	45.73	13.27	110.76	11.95	10.72
P_{29}	57.86	10.00	78.92	12.97	50.93	10.00	79.74	10.62	10.00	13.53	46.06	15.28
P_{30}	58.86	10.00	31.25	117.39	49.15	10.00	69.86	81.28	10.00	44.68	56.12	10.00
P_{31}	32.36	20.00	47.87	61.85	70.00	20.00	70.00	45.83	20.02	20.03	23.13	20.00
P_{32}	34.11	20.00	27.63	39.01	32.96	20.00	20.31	31.29	20.00	20.10	63.42	20.00
P_{33}	26.35	20.00	42.44	24.44	36.44	20.00	52.82	69.90	20.00	56.17	56.38	20.00
P_{34}	49.62	20.00	39.29	70.00	69.71	20.00	67.28	69.87	20.33	20.23	27.62	22.50
P_{35}	31.13	18.08	19.85	18.03	31.23	18.00	48.90	18.02	18.00	53.62	20.92	18.03
P_{36}	50.32	18.00	30.99	18.00	20.39	18.00	43.78	59.92	18.00	43.45	19.56	18.00
P_{37}	55.87	20.44	43.27	60.00	45.26	20.00	28.48	57.65	20.00	59.98	45.92	20.37
P_{38}	52.74	25.00	28.96	27.76	44.49	25.12	25.09	27.13	25.00	25.00	36.78	27.27
P_{39}	56.37	25.00	53.94	44.56	25.08	25.04	25.00	26.14	25.00	60.00	33.87	25.00
P_{40}	32.29	25.00	48.11	56.22	52.89	25.00	25.02	59.12	25.19	54.10	52.36	25.00
Fuel cost ($/h)	99702.72	103872.21	105526.46	113032.34	114453.65	115263.24	123015.95	123916.28	129301.09	133438.27	134237.31	144893.23
Time (s)	0.83	0.96	1.02	0.83	0.96	1.02	0.83	0.96	1.02	0.83	0.96	1.02

4.4. One hundred and forty unit system

A power system of Korea having 140 generating units with valve point loading effects is taken from the literature [29] as test system 4. The system comprising of 140 thermal generating units and twelve generators have the cost function with valve point loading effects and also four units have prohibited operating zones. The transmission losses are neglected for this test system. The input data of fuel cost are available in [29]. The total load demand is set to 49,342 MW. The best generation schedule obtained using CSA method is shown in Table 10. The convergence characteristic of 140 generators system obtained by CSA is shown in Fig. 17.

4.5. Three hundred and twenty unit system

A complex system with 320 thermal units with multiple fuel options and valve point loading effect is considered here. The system load demand is 86,400 MW. The input data of 10 units [29] are replicated up to 160 units and 320 units. The transmission loss is not included in the cost function. The cheapest generation schedule obtained using CSA is presented in Table 11. The convergence characteristic of 320 generators system obtained by CSA is shown in Fig. 18. The minimum, average, maximum fuel costs, standard deviation and execution time obtained by CSA method over 30 trials for test systems 140, 160 and 320 units are presented in

Table 9 Optimal cost of 40 unit system for valve point loading effect with various loads and their corresponding generation levels.

Load/generation	7550 MW	8550 MW	9550 MW	10,550 MW
P_1 (MW)	65.51	77.42	79.02	78.99
P_2 (MW)	99.06	99.28	120.00	119.99
P_3 (MW)	161.53	154.01	190.00	189.99
P_4 (MW)	24.86	24.22	24.41	41.99
P_5 (MW)	26.38	26.11	26.05	41.75
P_6 (MW)	107.52	139.99	139.99	140.00
P_7 (MW)	263.59	184.80	299.96	299.98
P_8 (MW)	213.67	284.56	290.81	300.00
P_9 (MW)	211.06	220.75	287.73	299.99
P_{10} (MW)	130.00	204.99	204.84	279.95
P_{11} (MW)	243.55	168.80	243.80	374.99
P_{12} (MW)	168.71	168.89	244.89	374.99
P_{13} (MW)	304.53	304.52	394.32	484.04
P_{14} (MW)	304.56	304.47	483.99	484.10
P_{15} (MW)	394.28	304.51	394.56	484.10
P_{16} (MW)	304.58	304.59	304.64	484.05
P_{17} (MW)	304.82	394.23	484.08	484.08
P_{18} (MW)	311.58	400.00	401.43	490.74
P_{19} (MW)	400.95	490.73	489.28	489.66
P_{20} (MW)	331.93	511.32	512.27	515.58
P_{21} (MW)	421.87	421.64	512.55	549.94
P_{22} (MW)	523.29	523.75	523.87	549.97
P_{23} (MW)	524.24	523.96	527.75	550.00
P_{24} (MW)	434.59	525.10	529.52	549.91
P_{25} (MW)	343.78	523.39	524.42	549.99
P_{26} (MW)	433.59	523.64	524.19	549.99
P_{27} (MW)	254.75	498.92	550.00	549.97
P_{28} (MW)	10.00	10.00	10.07	10.00
P_{29} (MW)	10.00	10.05	10.11	10.05
P_{30} (MW)	10.01	10.03	10.00	10.00
P_{31} (MW)	20.00	20.00	20.15	20.00
P_{32} (MW)	20.01	20.08	20.00	20.00
P_{33} (MW)	20.01	20.04	20.06	20.01
P_{34} (MW)	20.00	20.00	20.00	20.00
P_{35} (MW)	18.02	18.00	18.00	18.00
P_{36} (MW)	18.01	18.00	18.00	18.00
P_{37} (MW)	20.00	20.02	20.01	20.00
P_{38} (MW)	25.02	25.00	25.06	25.00
P_{39} (MW)	25.00	25.03	25.00	25.00
P_{40} (MW)	25.00	25.00	25.00	25.04
Fuel cost ($/h)	108401.72	118055.396	131654.62	147852.79

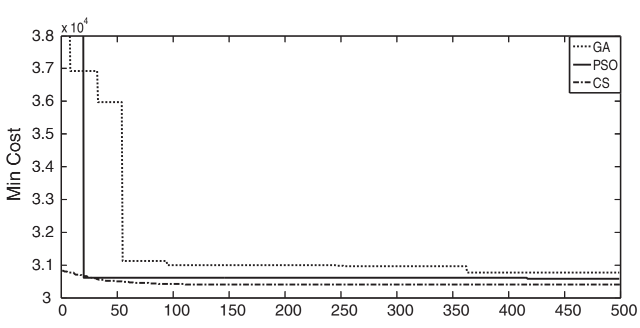

Figure 12 Convergence characteristics of evolutionary algorithms for 40 unit system with P_{LOAD} = 7550 MW.

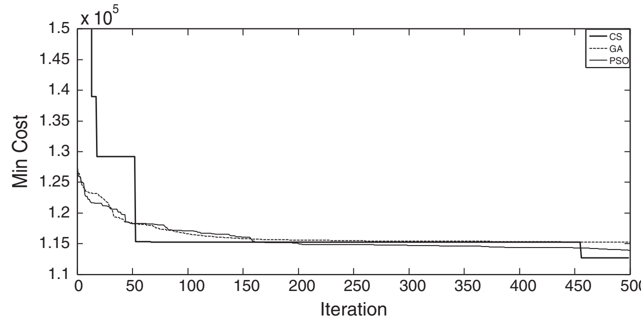

Figure 13 Convergence characteristics of evolutionary algorithms for 40 unit system with P_{LOAD} = 8550 MW.

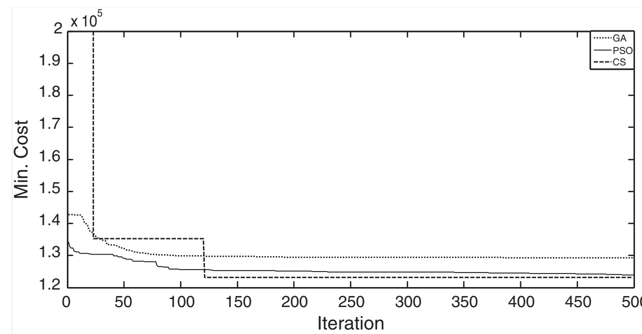

Figure 14 Convergence characteristics of evolutionary algorithms for 40 unit system with P_{LOAD} = 9550 MW.

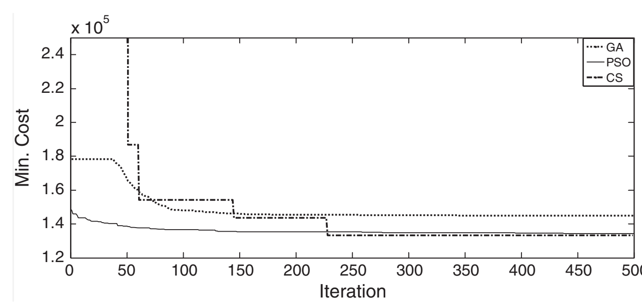

Figure 15 Convergence characteristics of evolutionary algorithms for 40 unit system with P_{LOAD} = 10,550 MW.

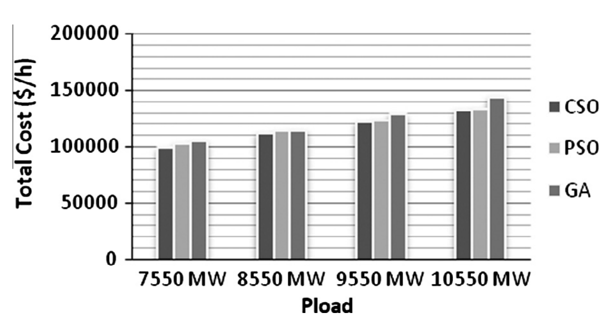

Figure 16 Comparison chart for 40 unit system for different load demands.

Table 10 Best power output for 140-generator system (P_D = 49,342 MW).

Unit	Power output MW	Unit	Power output MW	Unit	Power output MW	Unit	Power output MW	Unit	Power output MW
1	116.5000	29	501.0000	57	103.0000	85	115.0000	113	94.0000
2	189.0000	30	501.0000	58	198.0000	86	207.0000	114	94.0000
3	190.0000	31	506.0000	59	312.0000	87	207.0000	115	244.0000
4	190.0000	32	506.0000	60	289.0000	88	175.0000	116	244.0000
5	168.5000	33	506.0000	61	163.0000	89	175.0000	117	244.0000
6	190.0000	34	506.0000	62	95.0000	90	175.0000	118	95.0000
7	490.0000	35	500.0000	63	160.0000	91	175.0000	119	95.0000
8	490.0000	36	500.0000	64	160.0000	92	580.0000	120	116.0000
9	496.0000	37	241.0000	65	490.0000	93	645.0000	121	175.0000
10	496.0000	38	241.0000	66	196.0000	94	984.0000	122	2.0000
11	496.0000	39	774.0000	67	490.0000	95	978.0000	123	4.0000
12	495.9000	40	774.0000	68	490.0000	96	682.0000	124	15.0000
13	506.0000	41	3.0000	69	130.0000	97	720.0000	125	9.0000
14	509.0000	42	3.0000	70	234.7000	98	718.0000	126	12.0000
15	506.0000	43	250.0000	71	137.0000	99	720.0000	127	10.0000
16	505.0000	44	245.2000	72	325.5000	100	964.0000	128	112.0000
17	506.0000	45	250.0000	73	195.0000	101	958.0000	129	4.0000
18	506.0000	46	250.0000	74	175.0000	102	1007.0000	130	5.0000
19	505.0000	47	245.3000	75	175.0000	103	1006.0000	131	5.0000
20	505.0000	48	250.0000	76	175.0000	104	1013.0000	132	50.0000
21	505.0000	49	250.0000	77	175.0000	105	1020.0000	133	5.0000
22	505.0000	50	250.0000	78	330.0000	106	954.0000	134	42.0000
23	505.0000	51	165.0000	79	531.0000	107	952.0000	135	42.0000
24	505.0000	52	165.0000	80	531.0000	108	1006.0000	136	41.0000
25	537.0000	53	165.0000	81	376.8000	109	1013.0000	137	17.0000
26	537.0000	54	165.0000	82	56.0000	110	1021.0000	138	8.2000
27	549.0000	55	180.0000	83	115.0000	111	1015.0000	139	7.0000
28	549.0000	56	180.0000	84	115.0000	112	94.0000	140	33.4000
Fuel cost ($/h) = 1559547.4708								Load demand = 49342 MW	

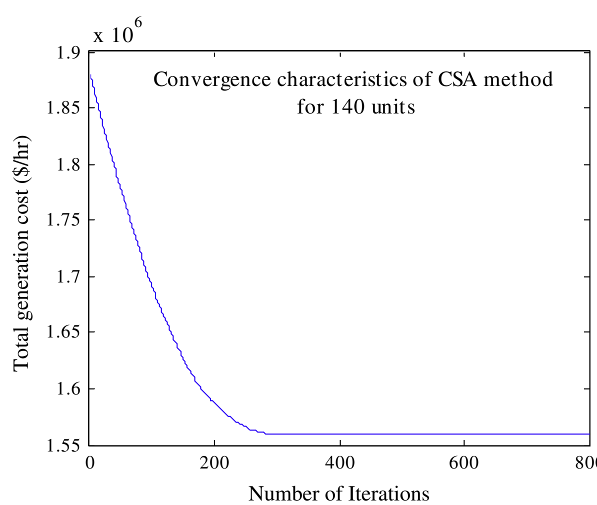

Figure 17 Convergence characteristics of Cuckoo search for 140 unit system.

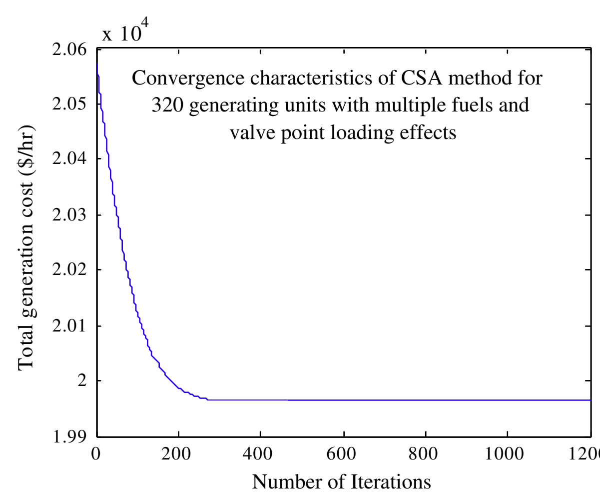

Figure 18 Convergence characteristics of Cuckoo search for 320 unit system.

Table 12. From this Table, one can see the effectiveness of the proposed CSA method in solving real world complex economic dispatch problems.

5. Conclusion

In this paper, while comparing the cost value for different evolutionary algorithms, Cuckoo Search algorithm comes out with the best result for each load value for six, fifteen, forty,

Table 11 Best power output for 320-generator system (P_D = 86,400 MW).

Unit	Power output MW	Unit	Power output MW	Unit	Power output MW	Unit	Power output MW	Unit	Power output MW	Unit	Power output MW
1	217.5691	55	276.5748	109	430.0676	163	279.6482	217	285.3793	271	217.5694
2	211.2162	56	239.9088	110	276.0139	164	240.1773	218	240.4455	272	211.2163
3	279.6481	57	285.3793	111	217.5692	165	276.5745	219	430.0674	273	279.6489
4	240.1771	58	240.4456	112	211.2162	166	239.9079	220	279.0155	274	240.1802
5	276.5748	59	430.0674	113	279.6490	167	285.3794	221	217.3645	275	276.9380
6	239.9080	60	279.0150	114	240.1801	168	240.4457	222	211.2162	276	239.9083
7	285.3794	61	217.3645	115	276.9380	169	430.0676	223	279.6483	277	285.3796
8	240.4457	62	211.2162	116	239.9085	170	278.8867	224	240.1770	278	240.4451
9	430.0675	63	279.6482	117	285.3796	171	217.5692	225	276.5741	279	430.0674
10	278.8868	64	240.1770	118	240.4449	172	211.2162	226	239.9080	280	279.0139
11	217.5692	65	276.5743	119	430.0674	173	279.6485	227	285.3793	281	217.5691
12	211.2162	66	239.9080	120	279.0139	174	240.1769	228	240.4453	282	211.2162
13	279.6485	67	285.3794	121	217.5692	175	276.5757	229	430.0672	283	279.6485
14	240.1770	68	240.4454	122	211.2162	176	239.9085	230	279.0143	284	240.1769
15	276.5757	69	430.0672	123	279.6489	177	285.3841	231	217.5692	285	276.5751
16	239.9085	70	279.0149	124	240.1769	178	240.4458	232	211.2162	286	239.9079
17	285.3841	71	217.5692	125	276.5750	179	430.0665	233	279.6482	287	285.3796
18	240.4457	72	211.2162	126	239.9081	180	279.0139	234	240.1770	288	240.4458
19	430.0665	73	279.6491	127	285.3792	181	217.5719	235	276.5741	289	430.0667
20	279.0140	74	240.1770	128	240.4458	182	211.2161	236	239.9090	290	279.0136
21	217.5719	75	276.5742	129	430.0668	183	279.6485	237	285.3798	291	217.5693
22	211.2161	76	239.9090	130	279.0139	184	240.1770	238	240.4457	292	211.2154
23	279.6485	77	285.3804	131	217.5693	185	276.5745	239	430.0673	293	279.6488
24	240.1770	78	240.4457	132	211.2156	186	239.9081	240	279.0673	294	240.1770
25	276.5745	79	430.0673	133	279.6481	187	285.3324	241	217.5697	295	276.5745
26	239.9081	80	279.0140	134	240.1771	188	240.4458	242	211.2160	296	239.9083
27	285.3316	81	217.5696	135	276.5743	189	430.0677	243	279.6481	297	285.3794
28	240.4458	82	211.2162	136	239.9082	190	279.0138	244	240.1770	298	240.4456
29	430.0677	83	279.6484	137	285.3795	191	217.5694	245	276.5744	299	430.0673
30	279.0138	84	239.9082	138	240.4457	192	211.5694	246	239.9103	300	279.0139
31	217.5694	85	276.5744	139	430.0673	193	279.6482	247	285.3800	301	217.5691
32	211.2163	86	239.9102	140	279.0141	194	240.1770	248	240.4456	302	211.2162
33	279.6484	87	285.3800	141	217.5691	195	276.5745	249	430.0674	303	279.6482
34	240.1770	88	240.4455	142	211.2161	196	239.9081	250	279.0144	304	240.1771
35	276.5745	89	430.0674	143	279.6484	197	285.3794	251	217.5693	305	276.5743
36	239.9081	90	279.0144	144	240.1771	198	240.4457	252	211.2162	306	239.9082
37	285.3792	91	217.5693	145	276.5743	199	430.0689	253	279.6484	307	285.3792
38	240.4457	92	211.2162	146	239.9082	200	279.0197	254	240.1770	308	240.4455
39	430.0689	93	279.6485	147	285.3792	201	217.5692	255	276.5747	309	430.0655
40	279.0195	94	240.1770	148	240.4456	202	211.2163	256	239.9082	310	279.0145
41	217.5692	95	276.5746	149	430.0655	203	279.6483	257	285.3794	311	217.5691
42	211.2163	96	239.9082	150	279.0146	204	240.1768	258	240.4457	312	211.2162
43	279.6484	97	285.3795	151	217.5689	205	276.5743	259	430.0679	313	279.6484
44	240.1768	98	240.4458	152	211.2162	206	239.9083	260	279.0145	314	240.1770
45	276.5746	99	430.0679	153	279.6482	207	285.3794	261	217.5692	315	276.5748
46	239.9083	100	279.0145	154	240.1770	208	240.4458	262	211.2164	316	239.9082
47	285.3794	101	217.5693	155	276.5749	209	430.0671	263	279.6483	317	285.3797
48	240.4458	102	211.2164	156	239.9081	210	279.0140	264	240.1770	318	240.4457
49	430.0674	103	279.6483	157	285.3798	211	217.5691	265	276.5744	319	430.0677
50	279.0141	104	240.1768	158	240.4458	212	211.2162	266	239.9080	320	279.0099
51	217.5691	105	276.5744	159	430.0676	213	279.6483	267	285.3794	Fuel cost	19964.171 ($/h)
52	211.2162	106	239.9082	160	279.0099	214	240.1784	268	240.4435		
53	279.6483	107	285.3794	161	217.5691	215	276.5746	269	430.0675		
54	240.1783	108	240.4432	162	211.2163	216	239.9088	270	279.0138		

one hundred and forty and three hundred and twenty unit power system. To verify the effectiveness and applicability of the proposed Cuckoo Search algorithm, constraints such as valve point loading, ramp rate limits, prohibited operating zones, multi-fuel options; start-up costs, power balance, generation limits and losses are also incorporated in the test system. The simulation is being carried out in MATLAB environment and the results are compared between three evolutionary algorithms. One can see the convergence nature of the proposed Cuckoo Search algorithm that shows better than other evolutionary algorithms. The reason behind the better convergence after a fixed number of iteration is that the less number of algorithm control parameters utilized. GA has failed to produce a better result than any of the algorithm in any case,

Table 12 Statistical results of CS algorithm taken after 30 trials for different test systems.

No of units	140	160	320
Minimum cost ($/h)	1559547.47	9982.085	19964.17
Average cost ($/h)	1559768.65	9985.42	19976.39
Maximum cost ($/h)	1559981.38	9996.87	19982.76
Std. deviation ($/h)	63.84	4.21	16.64
CPU time (s)	26.37	29.97	59.82

and since it is more preferable for binary-coded problems, GA has not been considered for the ultimate comparison. Since, the iteration value has been kept constant for both PSO and Cuckoo Search algorithms; it has not been taken into further consideration. PSO has four control parameters w_{max}, w_{min}, c_1, c_2 which can be varied for improving the objective function final value, and similarly, cuckoo search has only two control parameters which can be further varied for better results. So, the total combination of the control variables possible for PSO is factorial of four i.e. twenty-four whereas the total combination of the control variables possible for cuckoo search is factorial of two i.e. only two, thus making cuckoo search a better optimization converging algorithm compared to PSO. This fact proves and also it is evident from the results that Cuckoo Search algorithm is converging better than PSO and GA and also provides cheapest generation schedule, thus making it quite an efficient algorithm and less time consuming for online applications as well.

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