Chapter 6

Chemo-GA for Non-convex Economic Load Dispatch Problem

In this Chapter, the validation of CGAC is done for a real life application problem. It has been applied to Non-convex Economic load dispatch problem, where three Economic Load Dispatch (ELD) test systems have been considered including 3 generators, 13 generators and 40 generators. The three test systems have been solved taking into account the valve point effect and the results have been compared with Hybrid Chaotic PSO and Sequential Quadratic Programming (CPSO-SQP), Fire fly Algorithm, Genetic Algorithm Hybridized Bacterial Foraging Optimization (GA-BFO) and some other evolutionary algorithms.

Further the algorithm has also been applied to 15 generator system where all the operational constraints such as Power loss, Ramp rate limit and Prohibited Operating Zones constraints are taken into consideration and it has been further compared with recent state of the algorithm i.e. Iteration PSO (IPSO) and other algorithms also to test its efficacy.

6.1 INTRODUCTION

In the present day scenario, problems concerning the Load Dispatch of small, medium and large scale power systems are a robust optimization problem in modern power systems generally known as Economic Load Dispatch (ELD) problems. The core objective of the problem is determination of power output subject to minimum cost under a set of online generating units including all physical constraints and also taking into account all the operational constraints such as power loss, ramp rate limit, prohibited operating zones, valve point effect and generation limit constraints. Many deterministic optimization approaches are available in the literature for solving ELD problems. They are (i) Gradient Method (Dodu et al., 1972), (ii) Lagrangian Relaxation algorithm (Bard, 1988), (iii) Lambda iteration method (Chen and Wang, 1993), (iv) Linear programming (Parikh and Chattopadhay, 1996), (v) Dynamic programming (Lowery, 1996), (vi) Quadratic programming (Fan and Zhang, 1998) and many other methods.

The major drawback of such methods is that they are inappropriate to handle higher order nonlinearities. These methods also can not handle the discontinuities occurring in real input output characteristics of the generation cost function. They have the inherent drawback of being trapped into the local minima instead of global ones and also require enormous computational efforts to handle large scale ELD problem. In order to tackle such deficiencies of the deterministic approaches, several evolutionary computing methods came into existence such as GA (Chiang, 2007), Pattern Search Method (Al-Summait et al., 2007), Artificial Immune System (AIS) (Panigrahi et al., 2007), Chaotic PSO (Jiejin et al., 2007), PSO (Chaturvedi et al., 2009), Iteration PSO (IPSO) (Safari and Shayeghi, 2011), Firefly Algorithm (Yang et al., 2012), Quick Group Search Optimizer (QGSO) (Moradi-Dalvand et al., 2012), Gravitational Search Algorithm (GSA) (Swain et al., 2012), θ-PSO (Hosseinnezhad and Babaei, 2013), Interactive Honey Bee mating Optimization (IHBMO) (Ghasemi, 2013), and Kill Herd Algorithm (KHA) (Mandal et al., 2014).

In recent past, many popular hybrid methods were developed to tackle medium and large scale ELD problems with various operational constraints. To list a few, Hybrid (PSO-SQP), where PSO is hybridized with Sequential Quadratic Programming (Victoire and Jeyakumar, 2004), Hybrid Differential Evolution (HDE), the hybridization of Biogeography Based Optimization (BBO) and Differential Evolution (DE) (Bhattacharya and Chattopadhyay, 2011), Differential Harmony Search Algorithm (DHS) which is the hybridization of Differential Evolution (DE) and Harmony Search Algorithm (Wang and Li, 2013), Shuffled Differential Algorithm (SDE), the hybridization of Differential

Evolution and Shuffled frog leap Algorithm (Reddy and Vaisakh, 2013), DE based on PSO (DEPSO), the hybridization of DE and PSO (Sayah and Hamouda, 2013), hybrid PSO and Gravitational Search (HPSO-GSA) Algorithm (Jiang et al., 2014), where PSO is hybridized with the Gravitational Search Algorithm (GSA), and many other algorithms.

Inspired by several hybridization techniques to solve the ELD problems, in this Chapter, CGAC is applied to solve the following problem where four power system problems of Economic Load Dispatch of different generator constraints have been taken into account.

The rest of the Chapter is organized as follows. Strategies for handling constraints in the proposed CGAC are explained Section 6.2. Section 6.3 describes problem definition of Economic Load Dispatch (ELD). Methodology adopted in the Proposed CGAC Algorithm to solve ELD problem, the experimental set up and the corresponding result analysis for them are given in Section 6.4. The final conclusion of this Chapter is drawn in Section 6.5.

6.2 STRATEGIES FOR HANDLING CONSTRAINTS IN THE PROPOSED CGAC

The strategies for handling constraints are discussed in (Subsection 5.2.2, Chapter 5) which can be referred.

6.3 PROBLEM DEFINITIONS OF ELD PROBLEM WITH VALVE POINT LOADING EFFECT, RAMP RATE LIMIT AND POZ CONSTRAINTS

The objective of the ELD analysis is determination of the optimal combination of power generations by minimizing the total generation cost satisfying all generational constraints at the same time. They are (i) Quadratic cost function/ Quadratic cost function with valve point loading effect (ii) Power balance constraint, (iii) Generator capacity constraint, (iv) Power loss, (v) Ramp rate limits, (vi) Prohibited operating zones. The overall problem can then be formulated as a constrained optimization problem as follows. The Economic Load Dispatch problem can be modeled mathematically as Eq. (6.1)

$$MinF = \sum_{i=1}^{n} F_i(P_i) \tag{6.1}$$

Here F is the objective function describing the total generation cost. P_i is the power output of the i^{th} unit. $F_i(P_i)$ is the generation cost for the generator of unit i to produce power output P_i having quadratic cost function defined by Eq. (6.2). n is the number of committed units.

$$F_i = a_i P_i^2 + b_i P_i + c_i \tag{6.2}$$

Where a_i, b_i and c_i are the coefficients of generator i.

The generating units based on multi valve steam turbines are characterized by complex nonlinear fuel cost function. Such characteristics are happening due to the ripples induced during the valve point loading. The simulation of such phenomenon is done by super imposing the sinusoidal component on the quadratic heat rate curve. So, if the valve-point loading effect is taken into consideration, the sinusoidal terms are added to the quadratic cost function and modified generation cost $F_i(P_i)$ is defined as follows by Eq. (6.3)

$$F_i = a_i P_i^2 + b_i P_i + c_i + \left| e_i \sin\left(f_i \left(P_i^{\min} - P_i \right) \right) \right| \tag{6.3}$$

The fuel cost $F_i(P_i)$ is the sum of the quadratic function and the sinusoidal function. Where a_i, b_i and c_i are the coefficients of generator i. The coefficients e_i and f_i of unit i reflects the valve point effects. Here, P_i is the power output of the i^{th} generator. $P_i^{\min}$ is the minimum power output of the i^{th} generator.

The ELD problem is solved Subject to the following constraints:

(I) Generator capacity constraints:

The power output P_i of the i^{th} unit should vary within its minimum & maximum limits which is defined as Eq. (6.4)

$$P_i^{\min} \leq P_i \leq P_i^{\max} \tag{6.4}$$

Where $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum power output of the unit i.

(II) Power Balance constraint:

The power output P_i of the i^{th} unit defined in Eq. (6.4) is subject to the power balance constraint as defined in Eq. (6.5)

$$\sum_{i=1}^{n} P_i = P_D + P_L, \tag{6.5}$$

Where P_D is system load demand and P_L entire transmission network losses of the system. The power loss P_L is calculated by means of the B-coefficients matrix, which can be expressed as the quadratic function of unit' s power output defined as Eq (6.6).

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \tag{6.6}$$

Where, B_{ij} is the ij^{th} component of loss co-efficient square matrix of size n.

(III) Ramp rate limits

If the power increases, then

$$P_i - P_i^0 \leq UR_i \tag{6.7}$$

If the power decreases, then

$$P_i^0 - P_i \leq DR_i \tag{6.8}$$

Where P_i is the present power output of unit i. and P_i^0 is the previous power output of unit i. UR_i and DR_i are respectively the up-ramp and down-ramp limits of the i^{th} generator (in units of MW/time-period). The inclusion of the ramp rate limit included in the generator constraints as follows.

$$Max\left(P_i^{\min}, P_i^0 - DR_i\right) \leq P_i \leq Min\left(P_i^{\max}, P_i^0 + UR_i\right) \tag{6.9}$$

(IV) Prohibited Operating Zones:

The limitation of machine components and instability concerns of the operation zones impose certain restrictions on the generating units. So, the Prohibited operating zones can be mathematically formulated as follows.

$$\begin{cases} P_i^{\min} \leq P_i \leq P_{i,1}^{lb} \\ P_{i,j-1}^{ub} \leq P_i \leq P_{i,j}^{lb},\ j = 2,3,\ldots,nP_i \\ P_{i,j}^{ub} \leq P_i \leq P_i^{\max},\ j = nP_i \end{cases} \tag{6.10}$$

Where $P_{i,j}^{lb}$ is the lower bound and $P_{i,j}^{ub}$ is the upper bound of prohibited operating zone j of the generator i respectively. The total number of POZs of generator i is nP_i.

6.3.1 ELD problem of Four Test Cases

Firstly, the three test cases include 3, 13 and 40 generating units. The expected power demand to be met by all the 3 generating units is 850MW. The system data can be found from (Cai et al., 2012). The expected power demand to be met by all the 13 generating units is 2520MW. The system data can be found from (Cai et al., 2012). The expected power demand to be met by all the 40 generating units is 10500MW. The system data can be found from (Cai et al., 2012, Chaturvedi et al., 2008). The test cases consisting 3, 13 and 40 generators are solved taking into account the valve point loading effect with the Power balance constraint and Generator capacity constraint.

The fourth test case includes the 15 generating units and the expected power demand is 2630MW. The system data can be found from (Chaturvedi et al., 2008; Gaing, 2003). The fourth one is solved considering all the operational constraints i.e. Quadratic cost function, Generator capacity constraints, Power balance constraints, Power loss, Ramp rate limits, and Prohibited operating zones.

6.4 METHODOLOGY ADOPTED IN THE PROPOSED CGAC FOR SOLVING ELD PROBLEM

In the proposed CGAC method to solve ELD problem with valve point loading, ramp rate limit and POZ constraints the following three methodologies have been implemented. These are follows. (**i**) Calculation for slack generator, (**ii**) calculation of power output of dependent unit violating the capacity constraints, and (**iii**) handling the POZ constraints.

(I) Calculation of Slack Generator (Bhattacharya and Chattopadhyay, 2010)

Let P_n be the power output of the dependent generator.

$$P_n = P_D + P_L - \sum_{i=1}^{n-1} P_i \qquad (6.11)$$

Where the transmission loss is a function of all the generator outputs including the slack generator and it is given by

$$P_L = \sum_{i=1}^{n-1}\sum_{j=1}^{n-1} P_i B_{ij} P_j + 2P_n\left(\sum_{i=1}^{n-1} B_{ni} P_i\right) + B_{nn}P_n^2 + \sum_{i=1}^{n-1} B_{0i}P_i + B_{0n}P_n + B_{00} \qquad (6.12)$$

Substituting the power loss term P_L into Eq. (6.11), the quadratic equation obtained is given in Eq. (6.13)

$$B_{nn}P_n^2 + 2\left(\sum_{i=1}^{n-1} B_{ni}P_i + B_{0n} - 1\right)P_n + \left(P_D + \sum_{i=1}^{n-1}\sum_{j=1}^{n-1} P_i B_{ij} P_j + \sum_{i=1}^{n-1} B_{0i}P_i - \sum_{i=1}^{n-1} P_i + B_{00}\right) = 0 \tag{6.13}$$

It is a quadratic equation of the form

$$xP_n^2 + yP_n + z = 0, \text{ where } x = B_{nn} \tag{6.14}$$

$$y = \left(2\sum_{i=1}^{n-1} B_{ni}P_i + B_{0n} - 1\right) \tag{6.15}$$

$$z = \left(P_D + \sum_{i=1}^{n-1}\sum_{i=1}^{n-1} P_i B_{ij} P_j + \sum_{i=1}^{n-1} B_{0i}P_i - \sum_{i=1}^{n-1} P_i + B_{00}\right) \tag{6.16}$$

$$P_n = \frac{-y \pm \sqrt{y^2 - 4xz}}{2x} \tag{6.17}$$

where $y^2 - 4xz \geq 0$ (6.18)

If the inequality constraint Eq. (6.18) is violated then the power output of the generator are again reinitialized until the constraint Equation is satisfied including all other constraints of the problem concerned. If the Equation is still violated at later stage of the algorithm, the same procedure is repeated.

(II) Calculation of power output of dependent unit violating the capacity constraints

For the population of strings, if the power generation of the dependent unit P_n evaluated in Eq. (6.17) exceeds the maximum limit, calculate the differential amount,

$$Difference = P_n - P_n^{\max}. \tag{6.19}$$

Let $E = \dfrac{Differnce}{n-1}$ (6.20)

$$P_n = \begin{cases} P_n^{\min}, & if \ \ P_n < P_n^{\min} \\ P_n^{\max} and \ \ P_i = P_i + E \ \ for \ \ i = 1, 2, \ldots n-1, \\ if \ \ P_n > P_n^{\max} \end{cases} \quad (6.21)$$

If for any of the P_i^s, the generator capacity constraints Eq. (6.4) is violated, P_i is defined as follows.

$$P_i = \begin{cases} P_i^{\min}, if \ \ P_i \le P_i^{\min} \ \ for \quad i = 1, 2, \ldots, n-1 \\ P_i^{\max}, \ \ if \ \ P_i \ge P_i^{\max} \ for \quad i = 1, 2, \ldots, n-1 \end{cases} \quad (6.22)$$

(III) Handling of POZ constraints given (Yang et al., 2012).

Let power output P_i of i^{th} generator satisfying the POZ constraints is given by

$$P_{i,j}^{lb} \le P_i \le P_{i,j}^{ub} \quad (6.23)$$

Where $P_{i,j}^{lb}$ and $P_{i,j}^{ub}$ are the lower bound and upper bound of the j^{th} operating zone of the i^{th} generator.

Evaluate

$$P_{i,j}^{avg} = \left(\frac{P_{i,j}^{lb} + P_{i,j}^{ub}}{2} \right) \quad (6.24)$$

The power output P_i of i^{th} generator is defined as Eq. (6.25)

$$P_i = \begin{cases} P_{i,j}^{lb}, if \ \ P_{i,j}^{lb} \le P_i \le P_{i,j}^{avg} \\ P_{i,j}^{ub}, if \ \ P_{i,j}^{avg} \le P_i \le P_{i,j}^{ub} \end{cases} \quad (6.25)$$

6.4.1 Solution Methodology of the proposed CGAC for the ELD problem with Valve Point Loading, ramp rate limit and POZ constraints

The computational procedure for the ELD problem by CGAC technique can be described using the following steps.

***Step 1*:** Initialize the CGAC parameters and input parameters of the system. Specify the upper and lower boundaries of each variable.

Step 2: Randomly generate the power output of $n-1$ generators $P_1, P_2, P_3, ..., P_{n-1}$ satisfying the constraints Eq. (6.4), Eq. (6.7), Eq. (6.8), Eq. (6.9) and Eq. (6.10).

(a) Calculate x, y, z from Eq. (6.14), Eq. (6.15), and Eq. (6.16). Compute the power output of slack generator P_n from Eq. (6.17), satisfying the constraint defined as in Eq. (6.18).

(b) If the power output dependent unit P_n violates Eq. (6.4). Evaluate P_n and remaining power output of the generators by Eq. (6.19)-Eq. (6.22)

Step 3: Evaluate the Fitness function value of the ELD problem

$$Fit\_Fun = \sum_{i=1}^{n} F_i(P_i) + R\langle(g(x))\rangle^2 \tag{6.26}$$

Where the objective function value $F = \sum_{i=1}^{n} F_i(P_i)$ is taken as per Eq. (6.2) or Eq. (6.3) (If Valve loading effect is being considered). The penalty parameter R and bracket operator penalty function $\langle g(x)\rangle$ is taken from Eq. (5.5) and Eq. (5.4) respectively.

Evaluate the power loss P_L defined by Eq. (6.6). If the power loss is not considered, then the term $P_L = 0$.

Step 4: Apply Binary tournament selection operator to copy the best string maximum times as per Debs rule (Deb, 2000) defined in Step 3(Sub Section 5. 2. 2, Chapter 5).

Step 5: Apply Crossover operator to get better strings from the existing strings.

Step 6: Apply Mutation operator. Again compute the fitness function value as Eq. (6.26) and power loss as Eq. (6.6) as defined in (Step3).

Step 7: Apply Elitism operator and select the position of the best string and best fitness function value from the first half of the population.

Step 8: (a) Chemo tactic loop:

Initialize the search space as per Eq. (2.5), Eq. (2.6) (Section 2.4, Chapter 2) in the Chemo tactic loop and repeat ***Step 2.***

Evaluate the fitness function as defined in ***Step* 3.**

Update the position of the best string and best fitness function value

Compute Step sizes of Chemo tactic step as per Eq. (2.4), Eq. (2.7) (Section 2.4, Chapter 2).

The position of new search point in the Chemo tactic loop is computed as Eq. (5.6) (Section 5.3, Chapter 5).

Again, evaluate the fitness function as defined in ***Step* 3.**

Update the position of the best string and best fitness function value

(b) Swim loop:

Modify the searching point in the Swim loop defined as per Eq. (5.7) in the proposed algorithm CGAC given in (Section 5.3, Chapter 5).

Evaluate the fitness function as defined in ***Step* 3.**

Update the position of the best string and best fitness function value

Terminate the Swim loop if the maximum swim steps completed.

Terminate the Chemo tactic loop if Chemo tactic steps reached its upper limit.

Step 9: Repeat the process from ***Step 4*** until the maximum iteration is reached.

6.4.2. Experimental Setup

In this section Firstly three power systems having 3 generators, 13 generators and 40 generators have been considered with valve point loading effect considering the Generator capacity constraint and Power balance constraint. The results have been compared with Hybrid Chaotic PSO and Sequential Quadratic Programming (CPSO-SQP), Evolutionary Programming (EP), Evolutionary Programming and Sequential Quadratic Programming (EP-SQP), PSO, PSO and Sequential Quadratic Programming (PSO-SQP), Chaotic PSO (CPSO) and many other popular algorithms in terms of total generation cost, CPU time. Again the results have been compared in terms of best, average, worst function value, standard deviation, total number of function evaluation with Fire fly Algorithm and many other algorithms with whom the Fire Fly algorithm is being compared.

Again, all these problems also have been compared with GA-BFO in terms of function evaluation, CPU time, best, average, worst function value, standard deviation also.

Further to test the efficacy and robustness of the problem, it has been applied on 15 generator problem taking into consideration all the generator constraints such as Quadratic cost function, Ramp rate limit, Power loss, Prohibited operating zones etc. and the result has been compared with Iteration PSO (IPSO), GA, PSO, Different versions of Chaotic PSO (CPSO) i.e.CPSO1, CPSO2, Self-organizing Hierarchical PSO (SOH_PSO) etc.

For each problem, 100 independent runs are performed by keeping the following basic parameters fixed.

- **i.** Population size = 40
- **ii.** Number of Bacteria initialized in Chemo tactic loop= 4
- **iii.** The Probability of cross over (P_c)= 0.9

iv. Probability of mutation (P_m)= 0.001

v. Bit length (l)= 20

vi. The stopping criteria is either a maximum of 500 generations is attained or no improvement is observed in the best objective function value in consecutive 200 generations.

vii. The Chemo tactic loop is allowed after 10 generations for three generators. For 13 and 40 and 15 generators the loop is initialized after 40,700,100 generations respectively.

viii. Number of Chemo tactic steps= 40

ix. Number of swim steps= 4

The comparison of the result for 3, 13 and 40 generators in terms of mean cost, best cost and mean CPU time are reported in Table 6.1, Table 6.3 and Table 6.5 respectively. The best, average, worst function values, Standard Deviation, total no of function evaluation for 3 and 40 generators are mentioned in Table 6.2, Table 6.6 respectively. For the 13 generator power system, the comparison of the result of GA-BFO and CGAC in terms of success rate, best, average and worst function values, standard deviation, time and total no of function evaluation are given in Table 6.4. The success rate(S. R), best, average and worst function values, standard deviation(S.D), time and total no of function evaluation keeping the generation (500 fixed) and (1500 fixed) for forty generator are reported in Table 6.7, Table 6.8 respectively by varying the population size. The output of power generators in the best result of the proposed CGAC for the forty generators is shown in the Table 6.9(500 generation) and 6.10(1500 generation) respectively. Keeping the parameters fixed, the comparison graphs of GA-BFO and CGAC have been plotted for 3, 13 and 40 generators with valve point loading and shown in the Fig.6.1, 6.2 and 6.3 respectively. The best simulation for the 15 unit system with POZ constraints and ramp rate limits is shown in Table 6.11.

In all the tables, the bold face letters indicate the best result obtained by the corresponding mechanism/algorithm

Table 6.1: Best solutions of system 1(3 unit)) (Cai et al., 2012)

Method	P_1 **(MW)**	P_2 **(MW)**	P_3 **(MW)**	**Total generation cost($/h)**	**CPU time(sec)**
EP	300.264	400.000	149.736	**8234.07**	6.78
EP-SQP	300.267	400.000	149.733	**8234.07**	5.12
PSO	300.268	400.000	149.732	**8234.07**	4.37
PSO-SQP	300.267	400.000	149.733	**8234.07**	3.37
CPSO	300.267	400.000	149.733	**8234.07**	2.25
CPSO-SQP	300.266	400.000	149.734	**8234.07**	2.06
GA-BFO	300.264	400.000	149.736	**8234.07**	2.0472
CGAC	300.266	400.000	149.733	**8234.07**	**1.7866**

Table 6.2: The best, average and worst results of different ED solution methods for the 3-unit test system in terms of function evaluation (Yang et al., 2012)

Methods	**Generation cost($/h)**				
	Best	**Average**	**Worst**	**S.D**	**Noof function evaluation**
GAB	8234.08	NA	NA	NA	10,000
GAF	**8234.07**	NA	NA	NA	10,000
CEP	**8234. 07**	8235.97	8241.83	NA	**1000**
FEP	**8234. 07**	8234.24	8241.78	NA	**1000**
MFEB	**8234. 07**	8234.71	8241.8	NA	**1000**
IFEP	8234.08	8234.16	8234.54	NA	**1000**
FA	**8234.07**	**8234.08**	8241.23	3.63	5000
GA-BFO	**8234.07**	8249	8310.1	15.5337	1.09e+006
CGAC	**8234.07**	8235.25	**8240.91**	**2.5328**	22139

Table 6.3: Best solutions of system 2(13unit) (Cai et al., 2012)

Generator	Unit generation in MW								
	GA	SA	GA-SA	EP-SQP	PSO-SQP	CPSO	CPSO-SPQ	GA-BFO	CGAC
P_1	628.32	668.40	628.23	628.3136	628.3205	628.32	628.31	628.152	628.315
P_2	356.49	359.78	299.22	299.1715	299.0524	299.83	299.83	297.713	299.198
P_3	359.43	358.20	299.17	299.0474	298.9681	299.17	299.16	297.713	299.196
P_4	159.73	104.28	159.12	159.6399	159.4680	159.70	159.73	165.103	159.723
P_5	109.86	60.36	159.95	159.6560	159.1429	159.64	159.73	159.941	159.715
P_6	159.73	110.64	158.85	158.4831	159.2724	159.67	159.73	160.645	159.725
P_7	159.63	162.12	157.26	159.6749	159.5371	159.64	159.73	167.449	159.727
P_8	159.73	163.03	159.93	159.7265	158.8522	159.65	159.73	159.824	159.728
P_9	159.73	161.52	159.86	159.6653	159.7845	159.78	159.73	156.657	159.725
P_{10}	77.31	117.09	110.78	114.0334	110.9618	112.46	109.07	40.0782	77.3798
P_{11}	75.00	75.00	75.00	75.00	75.00	74.00	77.40	77.3021	77.3873
P_{12}	60.00	60.00	60.00	60.00	60.00	56.50	55.00	91.7889	92.39119
P_{13}	55.00	119.58	92.62	87.5884	91.6401	91.64	92.85	117.634	87.7637
Total	24,398.23	24,970.91	24,275.71	24,266.44	24,261.05	24,211.56	24,190.97	24,417.6	24,170.0392

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Table 6.4: Comparison of success rate (S.R), fun value, S.D, function evaluation between GA-BFO and CGAC for 13 unit system

Algorithm	S.R	Best value	Average value	Worst value	S.D	Time(s)	Fun value
GA-BFO	**100**	24,417.6	24793.3	24969	121.371	0.9428	65872
CGAC	**100**	**24,170.03929**	**24323.0157**	**24359.8**	**74.2326**	**0.8668**	**59437**

Table 6.5: Comparison of the total generation cost in system 3(40 unit) (Cai et al., 2012)

Method	Mean time(s)	Best cost($/h)	Mean cost($/h)
EP	1167.35	122,624.35	123,382.00
EP-SQP	997.73	122,323.97	122,379.63
PSO	933.39	123,930.45	124,154.49
PSO-SQP	733.97	122,094.67	122,245.25
GA-PS-SQP	46.98	121,458	122,039
CPSO	114.65	121,865.23	122,100.87
CPSO-SQP	98.49	121,458.54	122,028.16
GA-BFO	**25.1906**	121,598	121869
CGAC	51.5447	**120816.413**	**121309**

Table 6.6: The best, average and worst results of different ED solution in terms of function evaluation for the 40 unit test system) (Yang et al., 2012)

Methods	Generation cost($/h)				
	Best	Average	Worst	S.D	No. of function evaluation
HGPSO	124,797.13	126,855.70	NA	1160.91	NA
SPSO	124,350.40	126,074.40	NA	1153.11	NA
PSO	123,930.45	124,154.49	NA	NA	10,000
CEP	123,488.29	124,793.48	126902.89	NA	NA
HGAPSO	122,780.00	124,575.70	NA	906.04	NA
FEP	122,679.71	124,119.37	127245.59	NA	NA
MFEP	122,647.57	123,489.74	124356.47	NA	NA
IFEP	122,624.35	123,382.00	125740.63	NA	NA
TM	122,477.78	123,078.21	124693.81	NA	4050
EP-SQP	122,323.97	122,379.63	NA	NA	10000
MPSO	122,252.26	NA	NA	NA	NA
ESO	122,122.16	122,558.45	123,143.07	NA	75000
HPSOM	122,112.40	124,350.87	NA	978.75	NA
PSO-SQP	122,094.67	122,245.25	NA	NA	10000
PSO-LRS	122,035.79	122,558.45	123461.67	NA	20000
IMPROVED GA	121,915.93	122811.41	123334.00	NA	100000
HPSOWM	121,915.30	122844.40	NA	497.44	NA
IGAMU	121819.25	NA	NA	NA	NA
HDE	121813.26	122705.66	NA	NA	**100**
DEC(2)SQP(1)	121741.97	122295.12	122839.29	386.181	18000
PSO	121735.47	122513.91	123467.40	NA	20000
APSO(i)	121704.73	122,221.36	122995.09	NA	20000
ST-HDE	121,698.51	122304.30	NA	NA	**100**
NPSO-LRS	121664.43	122,209.31	122981.59	NA	20000
APSO(ii)	121663.52	122153.67	122912.39	NA	20000
SOHPSO	121501.14	121853.57	122446.30	NA	62500
BBO	121479.50	121512.06	121688.66	NA	50000
BF	121423.63	121814.94	NA	124.876	10000
GA-PS-SQP	121458.00	122039.00	NA	NA	1000
PS	121415.14	122332.65	125486.29	NA	1000
FA	121415.05	121416.57	121424.56	**1.784**	25000
GA-BFO	121598	121869	122077	156.148	31600
CGAC	**120816.413**	**121309**	**121810.14929**	109.675	73292

Table 6.7: Comparison of best, mean worst function value in terms of time and function evaluation varying population size in CGAC (Max gen=500)

Pop size	**S.R**	**Best value**	**Mean**	**Worst**	**S.D**	**Time(s)**	**Function evaluation**
200	**100**	120816.41350	121,309	121810.14929	109.675	**51.5447**	**73292**
400	**100**	121009.72185	121,201	121514.646044	103.07	143.83	107320
800	**100**	**120624.03503**	**121,104**	**121252.877466**	**94.7445**	698.917	253489

Table 6.8: Comparison of best, mean worst function value in terms of time and function evaluation varying population size in CGAC(Max gen=1500)

Pop. Size	**S.R**	**Best value**	**Mean**	**Worst**	**S.D**	**Time(s)**	**Function evaluation**
40	**100**	120681.156509	120900	121505	167.007	**32.9503**	**420040**
80	**100**	120610.526189	120864	120997.33010	131.339	42.2012	480080
100	**100**	120575.950677	120823	120999.9266	**107.121**	59.4816	510100
150	**100**	120549.105519	120761	121212.10551	180.527	119.076	585150
200	**100**	**120550.944596**	**120727**	**120937.44237**	136.779	190.334	647983

Table 6.9: Output power of generators in the best result of the proposed CGAC for the 40 unit test system in (500 iterations)

Unit	**Power(MW)**	**Unit**	**Power(MW)**
1	112.46837851377	**21**	523.606366735946
2	113.566474501022	**22**	524.281599313305
3	98.394564051022	**23**	523.906438737975
4	180.584211906587	**24**	526.356979710112
5	89.035333667093	**25**	523.232899887901
6	139.514815821588	**26**	523.745252366672
7	259.959707221718	**27**	523.4602245906172
8	284.3024390244	**28**	10.4602245906172
9	286.928402832608	**29**	10.1574136326231
10	130.502586843842	**30**	13.6266552228141
11	168.8178327735	**31**	92.0685454068619
12	167.890880480523	**32**	188.8835800967
13	214.575495314926	**33**	189.888543976299
14	395.423431799857	**34**	187.452132656415
15	303.693226522	**35**	166.56018882789
16	393.992561333057	**36**	165.295253081601
17	491.341849653355	**37**	91.573301862035
18	489.335393272222	**38**	108.825811220009
19	512.989771832746	**39**	109.851169444215
20	511.68853920777	**40**	510.70645685818
Total generation(MW)	10,500		
Generation cost($/h)	**120624.035031642**		

Table 6.10: (Output power of generators in the best result of the proposed CGAC for the 40 unit test system (1500 iterations)

Unit	Power(MW)	Unit	Power(MW)
1	111.85647378586	**21**	523.240803948258
2	110.412182247319	**22**	522.012851727391
3	97.1868106716195	**23**	524.276800419658
4	179.588460529772	**24**	524.729590158034
5	95.4948143909586	**25**	523.159787330412
6	139.870429869112	**26**	524.273977540929
7	299.673843072759	**27**	10.6575590682335
8	285.023446105388	**28**	11.5427604129404
9	284.569000786797	**29**	10.8503540519636
10	130.085115513935	**30**	90.8971938106398
11	94.1699010562	**31**	189.430570059367
12	94.392326729	**32**	189.742498152249
13	215.2131464129	**33**	188.626450182418
14	395.33760103	**34**	167.966850249125
15	394.416350761	**35**	164.536795174409
16	394.2911808883	**36**	170.227222659323
17	491.393386262251	**37**	109.818258112
18	489.307889278247	**38**	109.848089073256
19	510.838185156057	**39**	108.112543213407
20	511.141316548713	**40**	511.787183558548
Total generation(MW)	10,500		
Generation cost($/h)	**120549.105519167**		

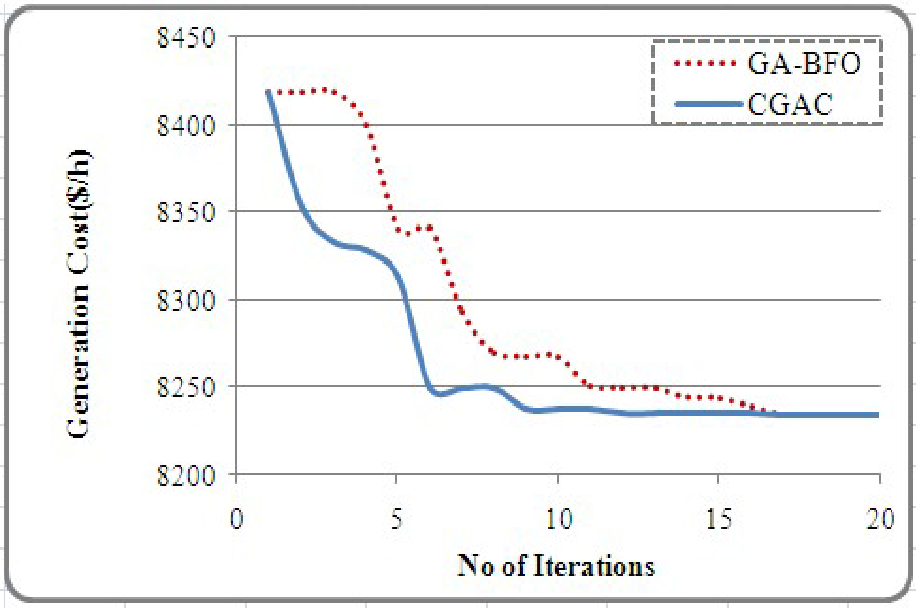

Fig.6.1. Convergence graph of 3 Generator

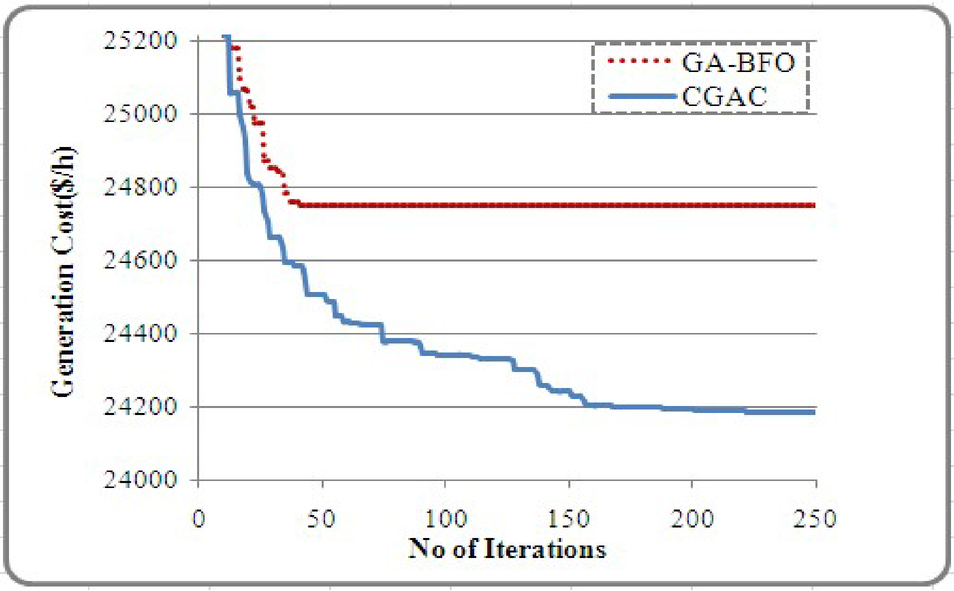

Fig.6.2. Convergence graph of 13 Generator

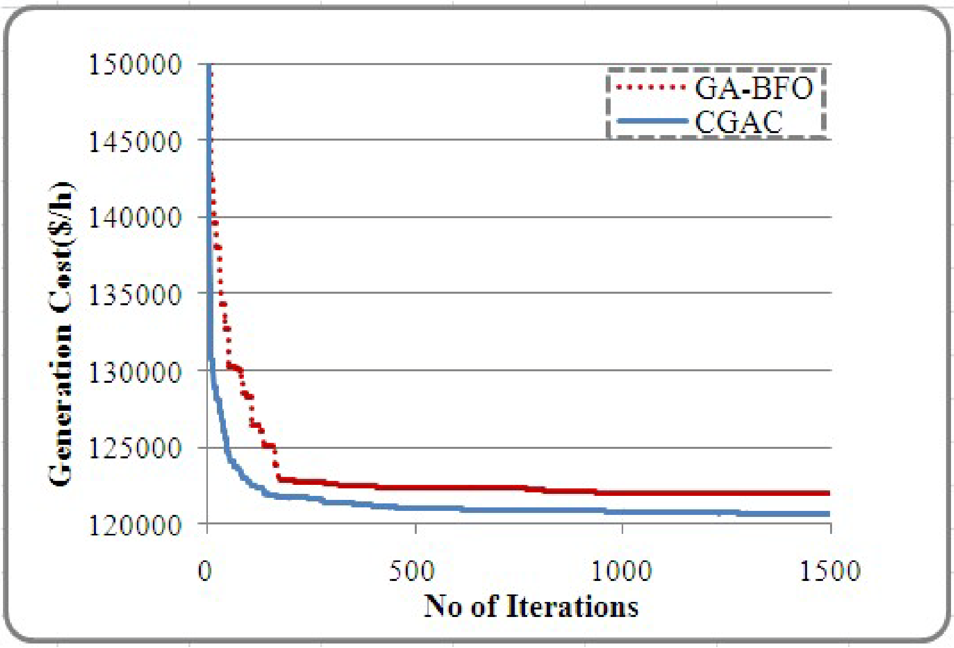

Fig.6.3. Convergence graph of 40 Generator

6.4.3 Result and Discussion

It can be visualized from the Table 6.1, 6.2, 6.3, 6.5, 6.6 and 6.11 that the best cost, mean cost and mean time are better in comparison to other algorithms mentioned in the table. It can be observed that CGAC also performs better in comparison to Genetic Algorithm Hybridized Bacterial Foraging Optimization (GA-BFO) in terms of success rate, best, average, worst function values, standard deviation, time and total no of function evaluations as can be observed from Table 6.1, 6.2, 6.3, 6.4, 6.5, 6.6 respectively. It can also be visualized from Fig.6.1, Fig.6.2 and Fig.6.3 that CGAC outperforms Genetic Algorithm Hybridized Bacterial Foraging Optimization (GA-BFO). Though the function evaluation is more, CGAC is performing better in terms of best, average, worst function value, mean time as compared to many popular continuous methods and hybridized algorithms listed in the table.

Table 6.11: Best simulation of 15 unit systems with POZ and ramp rate limits (Safari & Shayeghi, 2011)

Unit power output(MW)	**PSO**	**Hybrid GAPSO**	**CPSO1**	**CPSO2**	**SOH_PSO**	**IPSO**	**CGAC**
P_1	439.1162	436.8482	450.05	450.02	455.00	455.00	**454.9999**
P_2	407.9727	409.6974	454.04	454.06	380.00	380.00	**380**
P_3	119.6324	117.0074	124.82	124.81	130.00	129.97	**130**
P_4	129.9925	128.2705	124.82	124.81	130.00	130.00	**130**
P_5	151.0681	153.3361	151.03	151.06	170.00	169.93	**170**
P_6	459.9978	457.4078	460	460	459.96	459.88	**460**
P_7	425.5601	424.4400	434.53	434.57	430.00	429.25	**430**
P_8	98.5699	101.1949	148.41	148.46	117.53	60.43	**76.0148875**
P_9	113.4936	116.1186	63.61	63.59	77.90	74.78	**49.3533983**
P_{10}	101.1142	102.2243	101.13	101.12	119.54	158.02	**159.972272**
P_{11}	33.9116	35.0317	28.656	28.655	54.50	80.00	**80**
P_{12}	79.9583	78.8482	20.912	20.914	80.00	78.57	**80**
P_{13}	25.0042	27.1292	25.001	25.002	25.00	25.00	**25.00773494**
P_{14}	41.414	37.1594	54.418	54.414	17.86	15.00	**15.00777308**
P_{15}	35.614	37.0390	20.625	20.624	15.00	15.00	**20.0024973**
Total power output	2662.4	2661.75	2662.1	2662.1	2662.29	2660.8	**2660.3585**
Minimum cost($/h)	32858	32724	32835	32834	32751.39	32709	**32707.2428**
P_{loss}	32.4306	31.75	32.1302	32.1303	32.28	30.858	**30.358**
Mean cost($/h)	33039	32984	33021	33021	32878	32784.5	**32710.0588**

6.5 CONCLUSIONS

In this Chapter, Chemo-GA for constrained optimization (CGAC) has been successfully applied to ELD problem. Four test cases of ELD problems have been considered and solved by CGAC in which the parallel result is achieved with a conclusion that CGAC performs similar or better than Hybrid Chaotic PSO and Sequential Quadratic Programming (CPSO-SQP), Evolutionary Programming (EP), Evolutionary Programming and Sequential Quadratic Programming (EP-SQP), PSO, Sequential Quadratic Programming (PSO-SQP), Chaotic PSO(CPSO), Fire fly Algorithm, Genetic Algorithm Hybridized Bacterial Foraging Optimization(GA-BFO) and other popular and continuous methods available in literature. It is further realized that instead of hybridization of the entire BFO with GA, only the hybridization of Chemo tactic step with GA has a greater contribution towards the effectiveness and robustness of the CGAC algorithm in solving the real life problems i.e. ELD problems. It can be well visualized from the tabular results and convergence graphs of GA-BFO and CGAC. Therefore, the proposed hybrid algorithm CGAC is more reliable, more efficient and more accurate as compared to recent state of the art constrained evolutionary algorithms for solving non-convex ELD problems.