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Chemical reaction optimisation for different economic dispatch problems

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Abstract: This study presents a real coded chemical reaction algorithm to solve economic load dispatch (ELD) problems involving different constraints such as power balance, ramp rate limits and prohibited operating zone constraints. Effects of valve-point loading and multi-fuel options of large-scale thermal plants are also studied. System transmission loss has also been considered in a few cases. Chemical reaction optimisation mimics the interactions of molecules in a chemical reaction to reach from a higher energy unstable state to a low energy stable state. A real coded version, known as real-coded chemical reaction optimisation is implemented here to solve ELD problems. The simulation results establish that the proposed approach outperforms several other existing optimisation techniques in terms of quality of solution obtained and computational efficiency. The results also prove the robustness of the proposed methodology to solve ELD problems.

1 Introduction

Economic load dispatch (ELD) is the method of determining the most efficient, reliable and low-cost operation of a power system by dispatching the power generation resources to supply the load on the scheme. Its main objective is to minimise the total cost of generation while satisfying the operational constraints. Owing to the highly non-linear fuel cost characteristics of modern thermal power plants, the practical ELD problem contains many local optimum solutions and needs to consider a large number of complex constraints. Therefore the classical calculus-based methods [1] cannot perform very well in solving ELD problems, as these techniques need a smooth, differentiable objective function. Linear programming method [2] is fast and reliable but it has some drawbacks related with the piecewise linear cost approximation. Therefore dynamic programming (DP) approach was proposed by Wood and Wollenberg [3] to solve ELD problems. This technique does not impose any restriction on the nature of the cost curves, but suffers from the curse of dimensionality and larger simulation time.

In recent years, several attempts have been made to solve ELD with intelligent techniques, such as genetic algorithm (GA) [4], evolutionary programming (EP) [5], simulated annealing (SA) [6], particle swarm optimisation (PSO) [7], ant colony optimisation [8], differential evolution (DE) [9], artificial immune system [10], bacterial foraging algorithm [11], biogeography-based optimisation (BBO) [12] and so on. The above-mentioned techniques may prove to be very effective in solving non-linear ELD problems without any restriction on the shape of the cost curves. They often

provide a fast, reasonable nearly global optimal solution. However, these methods do not always guarantee global best solutions; rather they often achieve a near global optimal solution. Recently, different hybridisation and modification of GA, EP, PSO, DE and BBO like improved GA with multiplier updating (IGA-MU) [13], directional search GA (DSGA) [14], improved fast evolutionary programming [15], new PSO with local random search (NPSO_LRS) [16], adaptive PSO [17], self-organising hierarchical PSO [18], improved coordinated aggregation-based PSO [19], improved PSO [20], DE with generator of chaos sequences and sequential quadratic programming [21], variable scaling hybrid differential evolution [22], bacterial foraging with Nelder–Mead algorithm [23], hybrid differential evolution with BBO (DE/BBO) [24] and so on have been adopted to solve different types of ELD problems.

Evolutionary algorithms, swarm intelligence and bacterial foraging are all population-based bio-inspired algorithm. However, the common disadvantages of these algorithms are complicated computation and using many parameters. For that reason, it is also difficult to understand these algorithms for beginners.

In recent times, a new optimisation technique based on the concept of chemical reaction, called chemical reaction optimisation (CRO) has been proposed by Lam and Li [25]. In a chemical reaction, the molecules of the initial reactants stay in high-energy unstable states and undergo a sequence of collisions either with the walls of the container or with other molecules. The reactants pass through some energy barriers, reach low-energy stable states and become the final products. CRO captures this phenomenon of driving

high-energy molecules to stable, low-energy states, through various types of on-wall or inter-molecular reactions. CRO has been proved to be a successful optimisation algorithm in discrete optimisation. Basically, the CRO is designed to work in the discrete domain optimisation problems. To make this newly developed technique suitable for continuous optimisation domain, Lam *et al.* [26] have developed a real-coded version of CRO, known as real-coded CRO (RCCRO). It has been observed that the performance of the RCCRO is quite satisfactory when applied to solve the continuous benchmark optimisation problems. Recently, it has been applied to solve optimal V2G scheduling of electric vehicles and unit commitment problems [27]. In addition, optimal power flow problem has been solved using CRO [28]. The improved performance of the RCCRO to solve different optimisation problems has motivated the present authors to implement this newly developed algorithm to solve different non-convex complex ELD problems.

Section 2 of the paper provides a brief description and mathematical formulation of different types of ELD problems. Section 3 describes the proposed CRO algorithm along with a short description of the algorithm used in these test systems. Simulation studies are presented and discussed in Section 4. The conclusion is drawn in Section 5.

2 Mathematical modelling of the ELD problem

Four different types of ELD problems have been formulated and solved by the CRO approach. These are

2.1 ELD with quadratic cost function, ramp rate limit, prohibited operating zone and transmission loss

The overall objective function F_T of the ELD problem in this case, may be written as

$$F_T = \min \sum_{i=1}^N F_i(P_i) = \min \sum_{i=1}^N (a_i + b_i P_i + c_i P_i^2) \quad (1)$$

where $F_i(P_i)$, is the cost function of the i th generator, and is usually expressed as a quadratic polynomial; a_i , b_i and c_i are the cost coefficients of the i th generator; N is the number of committed generators; and P_i is the power output of the i th generator. The ELD problem consists of minimising F_T subject to the following constraints

2.1.1 Real power balance constraint:

$$\sum_{i=1}^N P_i - (P_D + P_L) = 0 \quad (2)$$

where P_L is the total transmission loss; and P_D is the total system active power demand. Calculation of P_L using the B -matrix loss coefficients is expressed as

$$P_L = \sum_{i=1}^N \sum_{j=1}^N P_i B_{ij} P_j + \sum_{i=1}^N B_{0i} P_i + B_{00} \quad (3)$$

2.1.2 Generating capacity constraint:

The power generated by each generator shall be within their lower limit

P_i^{\min} and upper limit P_i^{\max} so that

$$P_i^{\min} \leq P_i \leq P_i^{\max} \quad (4)$$

where P_i^{\min} and P_i^{\max} are the minimum and the maximum power outputs of the i th unit.

2.1.3 Ramp rate limit constraint: The power P_i generated by the i th generator in certain interval neither should exceed that of the previous interval P_{i0} by more than a certain amount UR_i the up-ramp limit and nor should it be less than that of the previous interval by more than some amount DR_i the down-ramp limit of the generator. These give rise to the following constraints:

As generation increases

$$P_i - P_{i0} \leq UR_i \quad (5)$$

As generation decreases

$$P_{i0} - P_i \leq DR_i \quad (6)$$

and

$$\max(P_i^{\min}, P_{i0} - DR_i) \leq \min(P_i^{\max}, P_{i0} + UR_i) \quad (7)$$

2.1.4 Prohibited operating zone: Generator prohibited operating zones mainly develop because of faults in the machines, boilers, feed pumps, steam valve operation, vibration in the shaft bearing and so on. The prohibited operation zone constraint is lying in between their maximum and minimum operating zone, that is, $P_i^{\min} < P_{i,k}^l < P_{i,k}^u < P_i^{\max}$. The output of a generator, P_i will not lie in a prohibited operation zone, if it satisfies any one of the conditions of the following equation

$$\begin{aligned} P_i^{\min} &\leq P_i \leq P_{i,1}^l \\ \text{or} \\ P_{i,k-1}^u &\leq P_i \leq P_{i,k}^l; \quad k = 2, 3, \dots n_i \\ \text{or} \\ P_{i,n_i}^u &\leq P_i \leq P_i^{\max} \end{aligned} \quad (8)$$

where k represents the number of prohibited operating zones of unit i . $P_{i,k}^u$ is the upper limit and $P_{i,k}^l$ is the lower limit of the k th prohibited operating zone of the i th unit. Total number of prohibited operating zones of the i th unit is n_i .

If it lies within any one of the prohibited operating zones, in that condition, P_i will be fixed to the nearest bound of the corresponding prohibited zone

$$\begin{aligned} P_i &= P_{i,k}^u \quad \text{if } P_{i,k}^u > P_i \geq (P_{i,k}^u + P_{i,k}^l)/2 \quad k = 2, 3, \dots n_i \\ &= P_{i,k}^l \quad \text{if } P_{i,k}^l < P_i < (P_{i,k}^u + P_{i,k}^l)/2 \quad k = 2, 3, \dots n_i \end{aligned}$$

2.2 ELD with quadratic cost function

The objective function of this type of ELD problem is the same as mentioned in (1). The objective function F_T is to be minimised subject to the constraints of (2), (4). Transmission loss is not considered.

2.3 ELD with valve-point effects, ramp rate limit and prohibited operating zone

The fuel cost function F_T in the ELD problem with valve point loading becomes more complex and is represented as follows

$$\begin{aligned} F_T &= \left(\sum_{i=1}^N F_i(P_i) \right) \\ &= \left(\sum_{i=1}^N a_i + b_i P_i + c_i P_i^2 + |e_i \times \sin\{f_i \times (P_i^{\min} - P_i)\}| \right) \end{aligned} \quad (9)$$

where e_i and f_i are the coefficients of the i th generator reflecting the valve-point effects. The objective function (9) is to be minimised subject to the set of constraints given in (4), (7) and (8).

2.4 ELD with non-smooth cost functions with multiple fuels and valve-point effects

For a power system with N generators and n_F fuel options for each unit, the cost function of the generator with valve-point loading is expressed as

$$\begin{aligned} F_{ip}(P_i) &= a_{ip} + b_{ip} P_i \\ &\quad + c_{ip} P_i^2 + |e_{ip} \times \sin\{f_{ip} \times (P_{ip}^{\min} - P_i)\}| \end{aligned}$$

if

$$\begin{aligned} P_{ip}^{\min} \leq P_i \leq P_{ip}^{\max} &\quad \text{for fuel option } p; \\ p = 1, 2, \dots, n_F \end{aligned} \quad (10)$$

where, P_{ip}^{\min} and P_{ip}^{\max} are the minimum and maximum power generation limits of the i th generator with fuel option p , respectively; a_{ip} , b_{ip} , c_{ip} , e_{ip} and f_{ip} are the fuel-cost coefficients of i th generator for fuel option p . Considering N is the number of generators, the objective function is to be minimised subject to the constraints of (2), (4) without transmission loss.

2.5 Calculation for slack generator

Let N committed generating units deliver their power output subject to the power balance constraint (2) and the respective capacity constraints of (4) and/or (7), (8). Assuming that the power loadings of the first $(N-1)$ generators are known, the power level of the N th generator (slack generator) is given by

2.5.1 Without transmission loss

$$P_N = P_D - \sum_{i=1}^{(N-1)} P_i \quad (11)$$

2.5.2 With transmission loss

$$P_N = P_D + P_L - \sum_{i=1}^{(N-1)} P_i \quad (12)$$

Using (3) and (12), the modified form of the equation is

$$\begin{aligned} B_{NN} P_N^2 &\left(2 \sum_{i=1}^{N-1} B_{Ni} P_i + \sum_{i=1}^{N-1} B_{0N} - 1 \right) \\ &+ \left(P_D + \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} P_i B_{ij} P_j + \sum_{i=1}^{N-1} B_{0i} P_i - \sum_{i=1}^{N-1} P_i + B00 \right) = 0 \end{aligned} \quad (13)$$

The solution procedure of (13) to calculate N th generator output, P_N is the same as mentioned in [24]. To avoid repetition it is not presented here.

3 Real-coded chemical reaction algorithm

This section presents an interesting new optimisation algorithm called CRO which has been recently proposed in [25, 26].

CRO loosely mimics what happens to molecules in a chemical reaction system. Every chemical reaction tends to release energy, therefore, the products generally have less energy than the reactants. In terms of stability, the lower the energy of the substance, the more stable it is. In a chemical reaction, the initial reactants in the high-energy unstable states undergo a sequence of collisions, pass through some energy barriers and become the final products in low-energy stable states. Therefore the products are always more stable than the reactants. It is not difficult to discover the correspondence between optimisation and chemical reaction. Both of them aim to seek the global optimum with respect to different objectives and the process evolves in a stepwise fashion. With this discovery, the chemical-reaction-inspired metaheuristic, called CRO [25] has been developed by Lam *et al.* in 2010.

This paper is the extension of CRO. CRO has been already proved to be a successful optimisation algorithm with different applications [25–29]. To make this optimisation technique suitable for both continuous and discrete optimisation problems, Lam *et al.* presented a modified version of CRO in 2012, which is termed RCCRO [26].

3.1 Major components of the RCCRO

Molecules: The manipulated agents involved in a reaction are known as molecules. Three main properties of each molecule are: (i) the molecular structure X ; (ii) current potential energy (PE); and (iii) current kinetic energy (KE); and some optional attributes which can be used to construct other versions of CRO for particular problems. The meanings of the attributes in the profile are given below:

Molecular structure: X actually represents the solution currently held by a molecule. Depending on the problem; X can be in the form of a number, an array, a matrix or even a graph. In this paper, the molecular structure has been represented in a matrix form.

Current PE: PE is the value of the objective function of the current molecular structure X , that is, $PE_X = f(X)$.

Current KE: KE provides the tolerance for the molecule to hold a worse molecular structure with higher PE than the existing one.

3.2 Elementary reactions

In CRO, several number of collisions occur. These collisions occur either between the molecules or between the molecules and the walls of the container. Depending upon the type of collisions, distinct elementary reactions occur, each of which may have a different way of controlling the energies of the involved molecule(s). There are four types of elementary reactions. These are: (i) on-wall ineffective collision; (ii) decomposition; (iii) intermolecular ineffective collision; and (iv) synthesis. On wall ineffective collision and decomposition are unimolecular reactions when the molecule hits a wall of the container. Inter-molecular ineffective collision and synthesis involve more than one molecule. Successful completion of an elementary reaction (subject to the energy limitation) results in an internal change of a molecule (i.e. updated attributes in the profile). In terms of optimisation, different elementary reactions explore the solution space in search for better solutions. Different types of elementary reactions are briefly described as follows.

3.2.1 On-wall ineffective collision: When a molecule hits a wall and bounces back, a small change occurs in its molecular structure and PE. As the collision is not so vigorous, the resultant molecular structure is not too different from the original one. If X and X' represent the molecular structure before and after the on-wall collision, respectively, then the on-wall ineffective collision tries to transform X to X' , in the close neighbourhood of X , that is

$$X' = X + \Delta \quad (14)$$

where Δ is a perturbation for the molecule. There are many probability distributions which can be used to produce probabilistic perturbations. In this paper, Gaussian distribution-based mutation operation of [15] (mainly (8) and (13) of [15]) has been employed, to transform X to X' , in the close neighbourhood of X . By the change of molecular structure, PE and KE also change from PE_X to $PE_{X'}$ and KE_X to $KE_{X'}$.

This change will happen only if (15) is satisfied

$$PE_X + KE_X \geq PE_{X'} \quad (15)$$

If (15) does not hold, the change is not allowed and the molecule retains its original X , PE and KE. Owing to interaction with a wall of the container, a certain portion of molecules' KE will be extracted and stored in the central energy buffer ('buffer') when the transformation is complete. The stored energy can be used to support decomposition. The size of the KE loss depends on a random number $a1 \in [KELossRate, 1]$, where $KELossRate$ is a parameter of CRO. Updated KE and buffer are represented as

$$KE_{X'} = (PE_X - PE_{X'} + KE_X) \times a1 \quad (16)$$

$$\text{buffer} = \text{buffer} + (PE_X + KE_X - PE_{X'}) \times (1 - a1) \quad (17)$$

It is possible for a molecule with lower PE to transform into one with higher PE, provided it has enough KE to begin with. After experiencing collision, the molecule has less KE. In this way, its tolerance of obtaining the worst solution is lowered and its ability of escaping from the local minima reduces.

3.2.2 Decomposition: In decomposition, one molecule hits the wall and breaks into two or more molecules, for example, X'_1 and X'_2 . Owing to the change of molecular structure, their PE and KE also changes from PE_X to $PE_{X'_1}$ and $PE_{X'_2}$, and KE_X to $KE_{X'_1}$ and $KE_{X'_2}$. This change is allowed, if the original molecule has sufficient energy (PE and KE) to endow the PE of the resultant ones, that is

$$PE_X + KE_X \geq PE_{X'_1} + PE_{X'_2} \quad (18)$$

$$\text{Let temp1} = PE_X + KE_X - PE_{X'_1} - PE_{X'_2}$$

then

$$KE_{X'_1} = k \times \text{temp1} \text{ and } KE_{X'_2} = (1 - k) \times \text{temp1} \quad (19)$$

where k is a random number uniformly generated from the interval $[0, 1]$. Equation (18) holds only when KE_X is large enough. Owing to the conservation of energy, X sometimes may not have enough energy (both PE and KE) to sustain its transformation into X'_1 and X'_2 . To encourage decomposition, a certain portion of energy, stored in the central buffer (buffer) can be utilised to support the change. In that case, the modified condition is

$$PE_X + KE_X + \text{buffer} \geq PE_{X'_1} + PE_{X'_2} \quad (20)$$

The new values of KE for the resultant molecules and buffer are

$$KE_{X'_1} = (\text{temp1} + \text{buffer}) \times m1 \times m2 \quad (21)$$

$$KE_{X'_2} = (\text{temp1} + \text{buffer}) \times m3 \times m4 \quad (22)$$

$$\text{buffer} = \text{buffer} + \text{temp1} - KE_{X'_1} - KE_{X'_2} \quad (23)$$

where the values of $m1, m2, m3$ and $m4$ are random numbers generated in between $[0, 1]$. To generate X'_1 and X'_2 , any mechanism which creates X'_1 and X'_2 quite different from X , is acceptable. However, in this paper, to generate X'_1 and X'_2 , the same procedure mentioned in Section 3.2 of [26] is followed.

3.2.3 Intermolecular ineffective collision: An intermolecular ineffective collision describes the situation when two molecules collide with each other and then bounce away. The effect of energy change of the molecules is similar to that in an on-wall ineffective collision, but unlike on-wall ineffective collision this elementary reaction involves more than one molecule and no KE is drawn to the central energy buffer. Similar to the on-wall ineffective collision, this collision is not vigorous, therefore, the new molecular structure is generated in the neighbourhood of the previous molecular structures. In this paper, new molecular structures are created using the same concept mentioned in the on-wall ineffective collision. Suppose the original molecular structures are X_1 and X_2 which are transformed after collision and two new molecular structures X'_1 and X'_2 , respectively, are formed. The two PE are changed from PE_{X_1} and PE_{X_2} to $PE_{X'_1}$ and $PE_{X'_2}$. The two KE are changed from KE_{X_1} and KE_{X_2} to $KE_{X'_1}$ and $KE_{X'_2}$. The changes to the molecules are acceptable only if

$$\text{PE}_{X_1} + \text{PE}_{X_2} + \text{KE}_{X_1} + \text{KE}_{X_2} \geq \text{PE}_{X'_1} + \text{PE}_{X'_2} \quad (24)$$

The new values of KE are calculated as

$$\begin{aligned} \text{KE}_{X'_1} &= (\text{PE}_{X_1} + \text{PE}_{X_2} + \text{KE}_{X_1} \\ &\quad + \text{KE}_{X_2} - \text{PE}_{X'_1} - \text{PE}_{X'_2}) \times aaa1 \end{aligned} \quad (25)$$

$$\begin{aligned} \text{KE}_{X'_2} &= (\text{PE}_{X_1} + \text{PE}_{X_2} + \text{KE}_{X_1} \\ &\quad + \text{KE}_{X_2} - \text{PE}_{X'_1} - \text{PE}_{X'_2}) \times (1 - aaa1) \end{aligned} \quad (26)$$

where $aaa1$ is a random number uniformly generated in the interval $[0, 1]$. If the condition of (24) fails, the molecules maintain the original X_1 , X_2 , PE_{X_1} , PE_{X_2} , KE_{X_1} and KE_{X_2} .

3.2.4 Synthesis: Synthesis is a process when two or more molecules (in the present paper two molecules X_1 and X_2) collide with each other and combine to form a single molecule X' . The change is vigorous and the resultant molecular structure X' is greatly different from X_1 and X_2 . As in decomposition, any mechanism which combines two molecules to form a single molecule may be used. In this paper, the procedure mentioned in Section 3.2 of [26] is used to create X' . The two PE are changed from PE_{X_1} and PE_{X_2} to $\text{PE}_{X'}$. The two KE are changed from KE_{X_1} and KE_{X_2} to $\text{PE}_{X'}$. The modification is acceptable if the following condition holds

$$\text{PE}_{X_1} + \text{PE}_{X_2} + \text{KE}_{X_1} + \text{KE}_{X_2} \geq \text{PE}_{X'} \quad (27)$$

The new value of KE of the resultant molecule is

$$\text{KE}_{X'} + \text{PE}_{X_1} + \text{PE}_{X_2} + \text{KE}_{X_1} + \text{KE}_{X_2} - \text{PE}_{X'} \quad (28)$$

If the condition of (27) is not satisfied, X_1 , X_2 and their related PE and KE are preserved, instead of X' , $\text{PE}_{X'}$ and $\text{KE}_{X'}$. The pseudocodes for all the above-mentioned elementary reaction steps are available in [25].

3.3 Sequential steps of the RCCRO algorithm

There are three stages in CRO: initialisation, iteration and the final stage. All the steps are mentioned as follows

In the initialisation stage, configure the initial settings for the molecules and the parameters (i.e. PopSize , KELossRate , MoleColl , buffer , InitialKE and α and β). Specify the number of unknown variables (n) and lower and upper bounds of the unknown variables of the given problem.

Create each molecule set, after generating all the unknown variables of the problem randomly within their effective lower and upper bounds, satisfying different constraints. Each molecule set represents a potential solution of the problem. Generate several molecule sets to create a molecular matrix, whose size is $(\text{PopSize} \times n)$.

Determine the PEs of each molecule set, by their corresponding objective function values. Set their initial KEs to InitialKE .

During the iterative process, first check the type of reaction to be held. Create a random number $b \in [0, 1]$. If b is greater than MoleColl or there is only one molecule left, the next reaction is a uni-molecular reaction, else it is an intermolecular reaction.

For each uni-molecular reaction, choose one molecule randomly and check whether it satisfies the decomposition criterion: (number of hits—minimum hit number) $> \alpha$ where α is the tolerance of duration for the molecule without obtaining any new local minimum solution. If so, perform the decomposition steps; else perform the on-wall ineffective collision steps.

For decomposition if (18) or (20) is satisfied, modify KE and buffer using (19) or (21), (22) and (23), respectively. Similarly for on-wall ineffective collision if (15) is satisfied then modify the KE and the buffer using (16) and (17), respectively. For both the cases, modify the PE of each molecule set by using their objective function value.

For each intermolecular reaction, select two (or more) molecule sets randomly from the molecular matrix and test the synthesis criterion: $(\text{KE} \leq \beta)$ where, β is the minimum KE a molecule should have.

If the condition is satisfied, perform the synthesis; otherwise, perform different steps of an intermolecular ineffective collision.

For synthesis if (27) is satisfied, modify the KE using (28). For intermolecular collision, if (24) is satisfied, modify the KE using (25) and (26). The PE of each modified molecule set is calculated in the same way as mentioned in step 5.

If the maximum number of iterations is reached or specified accuracy level is achieved, terminate the iterative process, otherwise go to step 4 for continuation.

3.4 RCCRO algorithm for ELD problem

In this subsection, the procedure to implement the RCCRO algorithm for solving the ELD problem has been described. The sequential steps of the RCCRO algorithm applied to solve the ELD problem are as follows.

3.4.1 Representation of the molecular structure

X : Since the assessment variables for the ELD problem are real power output of the generators, they are used to represent the individual molecular structure. Each individual element of the molecular structure represents the real power output of each generator. For the initialisations, choose the number of generator units m and the total number of molecular structure, PopSize .

The complete molecular structure is represented in the form of the following matrix

$$X = X_i = [X_1, X_2, X_3, \dots, X_{\text{PopSize}}]$$

$$\text{where } i = 1, 2, \dots, \text{PopSize}$$

In case of the ELD problem, each molecular set is represented as

$$\begin{aligned} X &= [X_{i1}, X_{i2}, \dots, X_{im}] [P_{g_{ij}}] \\ &= [P_{g_{i1}}, P_{g_{i2}}, \dots, P_{g_{im}}] \end{aligned}$$

where $j = 1, 2, \dots, m$. Each molecule set is one of the possible solutions for the ELD problem. The element X_{ij} of X_i is the j th position component of the molecule set i .

3.4.2 Initialisation of the molecule set: Each individual element of the molecular structure matrix, that is, each element of a given molecule set X , is initialised randomly within the effective real power operating limits. The initialisation is based on (4) for generators without ramp

rate limits, based on (4), (7) for generators with ramp rate limits and based on (4), (7), (8) for generators with ramp rate limits and prohibited operating zone.

3.4.3 Evaluation of PE: In case of the ELD problems, the PE, of each molecule set is represented by the total fuel cost of generation for all the generators of that given molecule set. It is calculated using (1) for the system having quadratic fuel cost characteristic; using (9) for the system having valve-point effect; and using (10) for the system having multi-fuel type fuel cost characteristic.

The steps of the algorithm to solve the ELD problems are given as follows:

Step 1: For initialisation, choose the number of generator units, m ; number of molecular structure set, $PopSize$; and elitism parameter ' p '. Specify the maximum and minimum capacity of each generator, power demand and B -coefficients matrix for calculation of transmission loss. Also, initialise the RCCRO parameters like $KELossRate$, $MoleColl$, $buffer$, $InitialKE$, α and β and so on. Set the maximum number of iterations, $Iter_{max}$.

Step 2: Initialise each element of a given molecule set of the X matrix using the concept mentioned in 'Initialisation of the Molecule set'. Each molecule set of the X matrix should satisfy the equality constraint of (2) using the concept of the slack generator mentioned in Section 2.5.

Step 3: Calculate the PE value for each molecule set of the habitat matrix for given initial KE $InitialKE$.

Step 4: Based on the PE values identify the elite molecule set. Here, the elite term is used to indicate those molecule sets of generator power outputs, which give the best fuel cost. Keep the top ' p ' molecule sets unchanged after individual iteration, without making any modification on it.

Step 5: Create a random number $b \in [0, 1]$. If b is greater than $MoleColl$ or if there is only one molecule left (at the later stage of the iterative procedure, this condition may hold), perform a unimolecular reaction, else perform an intermolecular reaction.

Step 6: If unimolecular reaction is selected, choose one molecule set randomly from the whole X matrix and check whether it satisfies the decomposition criterion.

If the decomposition condition is satisfied, perform decomposition on that particular molecule set. Create two new molecule sets using the steps mentioned in Section 3.2 of [26]. Calculate PE of the new molecule sets, using the concept mentioned in 'Evaluation of PE'. If the condition mentioned (18) or (20) is satisfied, modify KE of new molecule sets using (19) or (21), (22). Modify $buffer$ using (23).

If decomposition condition is not satisfied, perform on wall ineffective collision. Create two new molecule sets using Gaussian distribution and the procedure mentioned in Section 3.2.1. Calculate the PE of the modified molecule set. If the condition mentioned in (15) is satisfied then modify the KE of the new molecule set using (16). Modify the $buffer$ using (17).

Step 7: From the condition of step 5, if intermolecular reaction is chosen, select two (or more) molecule sets randomly from the molecular matrix X and test the synthesis criterion ($KE \leq \beta$).

If the condition is satisfied, perform the synthesis steps. Create a new molecule set from the two selected molecule sets following the procedure given in Section 3.2 of [26]. Calculate the PE of the new molecule set. After the new molecule creation, if the condition of (27) is satisfied, modify KE of new molecule set using (28).

If synthesis condition ($KE \leq \beta$) is not satisfied, perform intermolecular collision. Create two new molecule sets in the neighbourhood of selected molecule sets following Gaussian distribution and the procedure mentioned in Section 3.2.1. Calculate PE of the new molecule set. After new molecule sets creation, if the condition presented in (24) is satisfied, modify the KE of the new molecule sets using (25) and (26).

Step 8: Verify the feasibility of each newly generated molecule set of the modified X matrix, obtained after intermolecular or unimolecular reaction. The individual element of each modified molecule set must satisfy the generator operating limit constraint of (4). If some elements of a molecule set violate either the upper or lower operating limits, then fix the values of those elements of the molecule set at the limit hit by them. Satisfy the real power balance constraint of (2) [in case of lossless system take $P_L = 0$ in (2)] using the concept of the slack generator presented in Section 2.5. If the output of the slack generator does not meet the generator operating limit constraint (4) or some generators do not satisfy the prohibited operating zone or ramp rate limit constraints, where applicable; discard that new molecule set, and reapply the abovementioned steps 5 to 7 on its old value (before any molecular reaction was performed), until all the constraints are satisfied.

Step 9: Recalculate the PE of each newly generated molecule set, that is, the fuel cost for each power output set of each newly generated molecule set.

Step 10: Go to step 4 for the next iteration. Terminate the process after a predefined number of iterations, $Iter_{max}$.

4 Examples and simulation results

The proposed RCCRO algorithm has been applied to solve the ELD problems in four different test cases and its performance has been compared with several other optimisation techniques like GA [7], BBO, DE/BBO and PSO [7, 20] and so on for verifying its feasibility. All the programs of the RCCRO, BBO, DE/BBO and PSO algorithms have been executed on a 2.3-GHz Pentium IV personal computer with 1-GB RAM.

4.1 Description of the test systems

4.1.1 Test system 1: In this example, 15 generating units with ramp rate limit and prohibited zones constraints have been considered. Transmission loss has been included in the problem. Power demand is 2630 MW and system data have been taken from [7]. The results obtained from the proposed RCCRO, PSO [7] and different versions of PSO [20], BBO, DE/BBO and other methods have been presented here. Their best solutions are presented in Table 1. The convergence characteristic of the 15-generator systems in case of RCCRO, BBO and DE/BBO is shown in Fig. 1. Minimum, average and maximum fuel costs obtained by the RCCRO and different versions of PSO [20], BBO and DE/BBO over 50 trials are presented in Table 2.

4.1.2 Test system 2: A system with 38 generators with quadratic fuel cost characteristic is used here. The input data are available in [29]. The load demand is 6000 MW. Transmission loss has not been considered here. The result obtained using the proposed RCCRO method has been compared with BBO [24], DE/BBO [24], PSO-TVAC [24] and new-PSO [24]. Their best solutions are shown in

Table 1 Best power output for 15-generators systems ($P_D = 2630$ MW). Bold indicates best result

Units	RCCRO	GA [7]	PSO [7]	CTPSO [20]	CSPSO [20]	COPSO [20]	CCPSO [20]	BBO	DE/BBO
1	455.000000	415.3108	439.1162	455.0000	455.0000	455.0000	455.000000	455.000000	425.815607
2	380.000000	359.7206	407.9727	380.0000	380.0000	380.0000	380.0000	420.000000	419.480952
3	130.000000	104.4250	119.6324	130.0000	130.0000	130.0000	130.0000	130.000000	130.000000
4	130.000000	74.9853	129.9925	130.0000	130.0000	130.0000	130.0000	130.000000	127.109310
5	170.000000	380.2844	151.0681	170.0000	170.0000	170.0000	170.0000	270.000000	269.866995
6	460.000000	426.7902	459.9978	460.0000	460.0000	460.0000	460.000000	460.000000	459.155633
7	430.000000	341.3164	425.5601	430.0000	430.0000	430.0000	430.0000	430.000000	429.033732
8	72.952226	124.7867	98.5699	71.7430	71.7408	71.7427	71.7526	64.978264	69.906161
9	51.523013	133.1445	113.4936	58.9186	58.9207	58.9189	58.9090	47.684519	58.752044
10	152.434448	89.2567	101.1142	160.0000	160.0000	160.0000	160.0000	48.869702	80.549854
11	80.000000	60.0572	33.9116	80.0000	80.0000	80.0000	80.0000	59.049411	47.210600
12	80.000000	49.9998	79.9583	80.0000	80.0000	80.0000	80.0000	55.000000	73.165992
13	26.551796	38.7713	25.0042	25.0000	25.0000	25.0000	25.0000	26.853800	27.605892
14	17.151030	41.9425	41.4140	15.0000	15.0000	15.0000	15.0000	22.765547	15.494490
15	23.091567	22.6445	35.6140	15.0000	15.0000	15.0000	15.0000	36.953999	24.922918
total power, MW	2658.704080	2668.4	2662.4	2660.6615	2660.6615	2660.6615	2660.6616	2657.155242	2658.07018
power loss, MW	28.7041	38.2782	32.4306	30.6615	30.6615	30.6615	30.6616	27.15524143	28.0702
fuel cost, \$/h	32698.9950329897	33 113	32 858	32 704	327 04	32 704	32 704	32712.3959	32707.0296

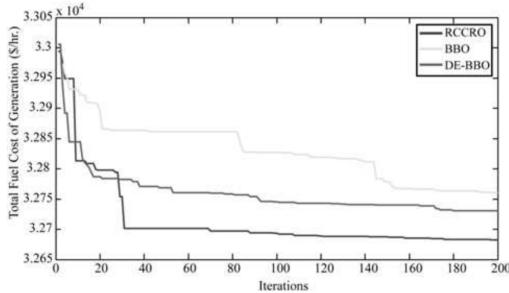
**Fig. 1** Convergence characteristic of 15-generators system obtained by RCCRO, BBO and DE/BBO

Table 3. The convergence characteristic of the 38-generators system in case of RCCRO, BBO and DE/BBO is shown in Fig. 2. Minimum, average and maximum fuel costs obtained by RCCRO, BBO, DE/BBO over 50 trials are presented in Table 4.

4.1.3 Test system 3: A 140 generators system having ramp rate limit and prohibited zone constraints are considered. The effect of valve-point loading has been incorporated within the generator fuel cost characteristics of

unit numbers 5, 10, 15, 22, 33, 40, 52, 70, 72, 84, 119 and 121. The input data of the whole system are taken from [20]. The load demand is 49 342 MW. The best results obtained by the proposed RCCRO are shown in Table 5. Out of 50 trials, minimum, maximum and average fuel cost obtained by using RCCRO, BBO, DE/BBO and different versions of PSO [20] are shown in Table 6. The convergence characteristic obtained using RCCRO, BBO and DE/BBO is presented in Fig. 3.

4.1.4 Test system 4: A complex system with 160 thermal units is considered here. The input data are available in [13]. The system demand is 43 200 MW. Transmission loss has not been included. The best result obtained using the proposed RCCRO algorithm is shown in Table 7. Minimum, average and maximum fuel costs obtained by RCCRO, ED-DE [30] and different GA [30] methods, BBO, DE/BBO over 50 trials are presented in Table 8. The convergence characteristic of the 160-generator systems obtained by RCCRO, BBO and DE/BBO is shown in Fig. 4.

4.2 Tuning of the parameters for the RCCRO algorithms

To obtain optimum solution using the RCCRO algorithm, it is necessary to obtain proper values of different parameters like, KE loss rate (*KELossRate*), initial KE (*InitialKE*) and β .

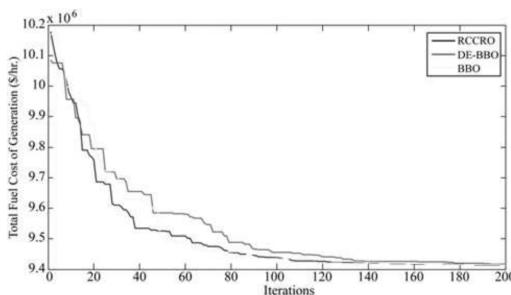
Table 2 Comparison between different methods taken after 50 trials (15-generators system). Bold indicates best result

Methods	Generation cost, \$/h			Time/iteration, s	No. of hits to minimum solution
	Max.	Min.	Average		
RCCRO	32698.9950329897	32698.9950329897	32698.9950329897	4.0	50
CTPSO [20]	32704.4514	32704.4514	32704.4514	22.5	NA ^a
CSPSO [20]	32704.4514	32704.4514	32704.4514	16.1	NA
COPSO [20]	32704.4514	32704.4514	32704.4514	85.1	NA
CCPSO [20]	32704.4514	32704.4514	32704.4514	16.2	NA
BBO	32713.4991	32712.3959	32712.528284	17.5	44
DE/BBO	32710.2396	32707.0296	32707.2864	12.4	46

^aNA – data not available

Table 3 Best power output for 38-generators system ($P_D = 6000$ MW). Bold indicates best result

Output, MW	RCCRO	DE/BBO [24]	BBO [24]	PSO_TVAC [24]	NEW_PSO [24]
P_1	426.006151	426.606060	422.230586	443.659	550.000
P_2	435.053969	426.606054	422.117933	342.956	512.263
P_3	422.447045	429.663164	435.779411	433.117	485.733
P_4	427.942500	429.663181	445.481950	500.00	391.083
P_5	432.575682	429.663193	428.475752	410.539	443.846
P_6	422.635559	429.663164	428.649254	492.864	358.398
P_7	431.182510	429.663185	428.119288	409.483	415.729
P_8	418.695906	429.663168	429.900663	446.079	320.816
P_9	115.065419	114.000000	115.904947	119.566	115.347
P_{10}	114.000000	114.000000	114.115368	137.274	204.422
P_{11}	122.192060	119.768032	115.418662	138.933	114.000
P_{12}	131.571421	127.072817	127.511404	155.401	249.197
P_{13}	110.000000	110.000000	110.000948	121.719	118.886
P_{14}	90.000000	90.000000	90.0217671	90.924	102.802
P_{15}	82.005966	82.000000	82.0000000	97.941	89.0390
P_{16}	120.124239	120.000000	120.038496	128.106	120.000
P_{17}	161.757829	159.598036	160.303835	189.108	156.562
P_{18}	65.000000	65.000000	65.0001141	65.0000	84.265
P_{19}	65.000000	65.000000	65.0001370	65.0000	65.041
P_{20}	271.946152	272.000000	271.999591	267.422	151.104
P_{21}	271.446566	272.000000	271.872680	221.383	226.344
P_{22}	258.558330	260.000000	259.732054	130.804	209.298
P_{23}	135.535741	130.648618	125.993076	124.269	85.719
P_{24}	10.000000	10.000000	10.4134771	11.535	10.000
P_{25}	115.305325	113.305034	109.417723	77.103	60.000
P_{26}	83.950616	88.0669159	89.3772664	55.018	90.489
P_{27}	39.681422	37.5051018	36.4110655	75.000	39.670
P_{28}	20.000000	20.000000	20.0098880	21.628	20.000
P_{29}	20.000000	20.000000	20.0089554	29.829	20.995
P_{30}	20.005560	20.000000	20.0000000	20.326	22.810
P_{31}	20.000374	20.000000	20.0000000	20.000	20.000
P_{32}	20.000000	20.000000	20.0033959	21.840	20.416
P_{33}	25.000273	25.000000	25.0066586	25.620	25.000
P_{34}	18.000000	18.000000	18.0222107	24.261	21.319
P_{35}	8.000000	8.0000000	8.00004260	9.6670	9.1220
P_{36}	25.000000	25.000000	25.0060660	25.000	25.184
P_{37}	23.727555	21.7820891	22.0005641	31.642	20.000
P_{38}	20.827629	21.0621792	20.6076309	29.935	25.104
fuel cost, \$/h	9412404.27 74250172	9417235.78 6391673	9417633.6 376443729	9500448.307	9516448.312

**Fig. 2** Convergence characteristic of 38-generators system obtained by RCCRO, BBO and DE/BBO

Tuning of other RCCRO parameters like *MoleColl* and α are also very important. For different values of these parameters, minimum fuel costs of generation are evaluated for the 160 generators system. For a single value of one parameter, the other parameters have been varied for all their possible combinations. As for example, when *InitialKE* = 2000; time β has been varied from 100 to 1000 in suitable steps. At the same time for each value of β , α has been varied from 100 to 2000 in suitable steps. Similarly, for each value of α , *MoleColl* and *KELossRate* have been varied from 0.1 to 0.9. However, to present all these results in a table, takes lots of space. Therefore the detailed tuning procedure is not presented here. A brief summarised result is only shown in Table 9.

Too large or small value of the molecular structure size may not be capable of obtaining the minimum value of fuel

Table 4 Comparison of maximum, minimum and average value taken after 50 trials (38-generators system). Bold indicates best result

Methods	Generation cost, \$/h			Time/iteration, s	No. of hits to minimum solution
	Max.	Min.	Average		
RCCRO	9412404.27 74250172	9412404.27 74250172	9412404.27 74250172	0.62	50
BBO	9417658.75 20243911	9417633.63 76443729	9417638.15 823277617	12.12	41
DE/BBO	9417250.8 3217432	9417235.7 86391673	9417237.29 09699377	17.75	45

Table 5 Best power output for 140-generators system ($P_D = 49342$ MW)

Units	Power output, MW	Units	Power output, MW	Units	Power output, MW
P_1	118.635523	P_{48}	249.269876	P_{95}	837.500000
P_2	163.993075	P_{49}	249.413942	P_{96}	682.000000
P_3	189.984436	P_{50}	248.351325	P_{97}	720.000000
P_4	189.891409	P_{51}	166.994790	P_{98}	718.000000
P_5	168.470912	P_{52}	165.044151	P_{99}	720.000000
P_6	189.830191	P_{53}	167.258619	P_{100}	964.000000
P_7	490.000000	P_{54}	168.370545	P_{101}	957.999999
P_8	490.000000	P_{55}	180.159717	P_{102}	947.900000
P_9	496.000000	P_{56}	180.287733	P_{103}	933.999999
P_{10}	495.992088	P_{57}	106.611337	P_{104}	935.000000
P_{11}	496.000000	P_{58}	198.088089	P_{105}	876.500000
P_{12}	496.000000	P_{59}	311.592155	P_{106}	880.900000
P_{13}	506.000000	P_{60}	307.044355	P_{107}	873.700000
P_{14}	509.000000	P_{61}	163.045884	P_{108}	877.400000
P_{15}	506.000000	P_{62}	95.122064	P_{109}	871.700000
P_{16}	505.000000	P_{63}	510.896670	P_{110}	864.800000
P_{17}	506.000000	P_{64}	510.794516	P_{111}	881.999999
P_{18}	506.000000	P_{65}	489.996261	P_{112}	94.170375
P_{19}	505.000000	P_{66}	252.809906	P_{113}	94.021855
P_{20}	505.000000	P_{67}	489.676926	P_{114}	94.034733
P_{21}	505.000000	P_{68}	490.000000	P_{115}	244.046810
P_{22}	505.000000	P_{69}	130.563498	P_{116}	244.030385
P_{23}	504.999740	P_{70}	339.449200	P_{117}	244.003786
P_{24}	505.000000	P_{71}	148.596570	P_{118}	95.028007
P_{25}	537.000000	P_{72}	388.259590	P_{119}	95.029435
P_{26}	537.000000	P_{73}	197.568348	P_{120}	116.064059
P_{27}	549.000000	P_{74}	188.360629	P_{121}	175.117844
P_{28}	549.000000	P_{75}	183.283938	P_{122}	2.008743
P_{29}	501.000000	P_{76}	272.809084	P_{123}	4.037426
P_{30}	499.000000	P_{77}	383.575174	P_{124}	15.043739
P_{31}	505.999959	P_{78}	340.711902	P_{125}	9.302986
P_{32}	506.000000	P_{79}	530.999999	P_{126}	12.163916
P_{33}	505.999999	P_{80}	530.999998	P_{127}	10.004659
P_{34}	506.000000	P_{81}	541.999727	P_{128}	112.100487
P_{35}	500.000000	P_{82}	56.022438	P_{129}	4.101433
P_{36}	500.000000	P_{83}	115.049472	P_{130}	5.046108
P_{37}	241.000000	P_{84}	115.007300	P_{131}	5.002875
P_{38}	240.999596	P_{85}	115.010039	P_{132}	50.020513
P_{39}	774.000000	P_{86}	207.051799	P_{133}	5.018295
P_{40}	769.000000	P_{87}	207.064542	P_{134}	42.025383
P_{41}	3.050172	P_{88}	176.983104	P_{135}	42.000018
P_{42}	3.004400	P_{89}	177.795032	P_{136}	41.071858
P_{43}	249.970693	P_{90}	177.076118	P_{137}	17.002006
P_{44}	249.707274	P_{91}	175.135128	P_{138}	7.035482
P_{45}	249.975946	P_{92}	575.400000	P_{139}	7.093464
P_{46}	249.204175	P_{93}	547.500000	P_{140}	26.346630
P_{47}	248.015616	P_{94}	836.800000	Cost (\$/h)	1657690.8383422962

cost. For each molecular structure size ($PopSize$) of 20, 50, 100, 150 and 200, 50 trials have been run. Out of these, the molecular structure size of 50 achieves the best fuel cost of generation for this system. For other molecular structure size, no significant improvement of the fuel cost has been observed. Moreover, beyond $PopSize = 50$, the simulation

time also increases. The best output obtained by the RCCRO algorithm for each molecular structure size is presented in Table 10.

Therefore, optimum values of these tuned parameters are $PopSize = 50$, $InitialKE = 600$, $KELossRate = 0.8$, $\beta = 300$, $MoleColl = 0.2$ and $\alpha = 300$. The initial value of $buffer = 0$

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Table 6 Comparison between different methods taken after 50 trials (140-generators system). Bold indicates best result

Methods	Generation cost, \$/h			Time/iteration, s	No. of hits to minimum Solution
	Max.	Min.	Average		
RCCRO	1657742.9759776704	1657690.8383422962	1657693.966600419	75.8	47
CTPSO [20]	1658002.79	1657962.73	1657964.06	100	NA
CSPSO [20]	1657962.85	1657962.73	1657962.74	99	NA
COPSO [20]	1657962.73	1657962.73	1657962.73	150	NA
CCPSO [20]	1657962.73	1657962.73	1657962.73	150	NA
BBO	1657809.5740158	1657724.388156	1657739.721611	142.5	41
	720	7011	351862		
DE/BBO	1657781.7243158120	1657716.8431887494	1657725.926546538164	125.4	43

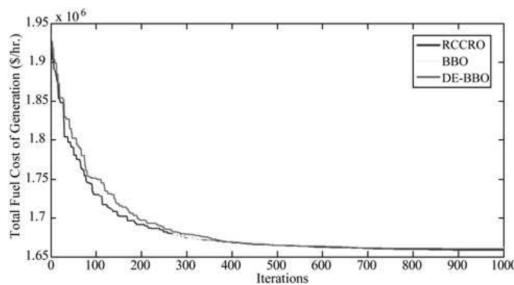


Fig. 3 Convergence characteristic of 140-generators system, obtained by RCCRO, BBO and DE/BBO

is not selected by using the tuning procedure; rather its value is assumed based on the value presented in Section 2.3 of [26].

4.3 Comparative study

4.3.1 Solution quality: Tables 1, 3, 5 and 7 present the best fuel cost obtained by the RCCRO for four different test systems. These costs are better compared with the results obtained by many previously developed techniques specially recently developed techniques like BBO and DE/BBO. These are also shown in Tables 2, 4, 6 and 8. These tables also represent the comparative studies for maximum, minimum and average values, obtained by different

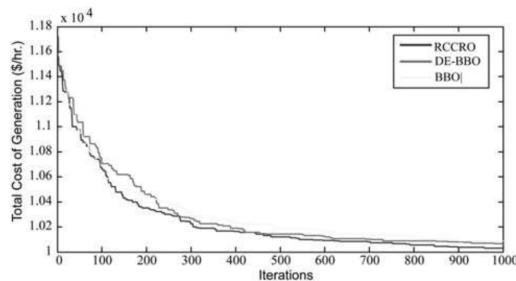
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Table 7 Best power output for 160-generators system ($P_D = 43\,200$ MW). Bold indicates best result

Units	Power output, MW	Units	Power output, MW	Units	Power output, MW
P_1	228.512956	P_{55}	271.020575	P_{109}	433.252001
P_2	213.141482	P_{56}	235.883901	P_{110}	273.119626
P_3	285.251836	P_{57}	273.841949	P_{111}	216.141555
P_4	237.000044	P_{58}	238.755448	P_{112}	213.628701
P_5	282.837491	P_{59}	423.217864	P_{113}	286.584654
P_6	240.650011	P_{60}	271.181299	P_{114}	238.345769
P_7	293.660960	P_{61}	207.635270	P_{115}	269.954240
P_8	240.075393	P_{62}	204.476587	P_{116}	239.376575
P_9	419.338555	P_{63}	292.617568	P_{117}	290.993670
P_{10}	263.540637	P_{64}	237.266613	P_{118}	236.967088
P_{11}	220.599052	P_{65}	285.105650	P_{119}	410.713095
P_{12}	208.823182	P_{66}	240.838033	P_{120}	267.344063
P_{13}	277.475022	P_{67}	298.784930	P_{121}	219.493657
P_{14}	239.490067	P_{68}	237.281670	P_{122}	211.302813
P_{15}	276.400584	P_{69}	433.680524	P_{123}	277.675606
P_{16}	235.359029	P_{70}	275.520867	P_{124}	240.613698
P_{17}	287.948673	P_{71}	221.176273	P_{125}	269.774597
P_{18}	244.729509	P_{72}	213.477004	P_{126}	241.031533
P_{19}	422.676933	P_{73}	277.539752	P_{127}	282.402024
P_{20}	266.958762	P_{74}	246.389791	P_{128}	237.751251
P_{21}	234.426423	P_{75}	262.871434	P_{129}	428.341747
P_{22}	211.085922	P_{76}	236.293917	P_{130}	276.742465
P_{23}	493.369468	P_{77}	290.631771	P_{131}	224.284756
P_{24}	242.768901	P_{78}	243.330312	P_{132}	209.470708
P_{25}	278.618288	P_{79}	426.926094	P_{133}	276.176336
P_{26}	238.306043	P_{80}	272.056387	P_{134}	238.006990
P_{27}	272.986434	P_{81}	246.348501	P_{135}	276.228838
P_{28}	244.541712	P_{82}	212.389337	P_{136}	237.877156
P_{29}	439.732394	P_{83}	288.528805	P_{137}	267.418357
P_{30}	260.001738	P_{84}	241.200263	P_{138}	239.812695
P_{31}	214.749072	P_{85}	270.189356	P_{139}	421.887374
P_{32}	209.588194	P_{86}	241.112752	P_{140}	274.294730
P_{33}	276.185024	P_{87}	282.841621	P_{141}	234.605996
P_{34}	236.934663	P_{88}	241.929344	P_{142}	212.852842
P_{35}	279.089320	P_{89}	425.522354	P_{143}	281.140182
P_{36}	244.403487	P_{90}	271.668698	P_{144}	243.487020
P_{37}	284.397223	P_{91}	218.224630	P_{145}	276.315063
P_{38}	236.213533	P_{92}	215.692373	P_{146}	241.750796
P_{39}	431.744652	P_{93}	287.571621	P_{147}	295.350666
P_{40}	263.683291	P_{94}	240.002417	P_{148}	241.567640
P_{41}	215.660924	P_{95}	279.345447	P_{149}	351.010838
P_{42}	214.072349	P_{96}	239.404781	P_{150}	281.481661
P_{43}	285.506648	P_{97}	271.226563	P_{151}	222.414824
P_{44}	240.512220	P_{98}	241.841628	P_{152}	213.395010
P_{45}	270.343916	P_{99}	420.759969	P_{153}	275.247355
P_{46}	236.571125	P_{100}	279.985946	P_{154}	239.125949
P_{47}	290.739072	P_{101}	220.936433	P_{155}	274.853925
P_{48}	236.747167	P_{102}	212.490751	P_{156}	238.607039
P_{49}	434.928202	P_{103}	274.647444	P_{157}	277.032342
P_{50}	269.598859	P_{104}	241.187432	P_{158}	242.243508
P_{51}	214.153580	P_{105}	274.560262	P_{159}	430.588550
P_{52}	211.639997	P_{106}	239.638377	P_{160}	262.076486
P_{53}	276.870998	P_{107}	285.864021	Cost, \$/h	10009.5183
P_{54}	241.402520	P_{108}	238.887792		

Table 8 Comparison between different methods taken after 50 (160-generators system). Bold indicates best result

Methods	Generation cost, \$/h			Time/iteration, s	No. of hits to minimum solution
	Max.	Min.	Average		
RCCRO	10009.5827	10009.5183	10009.5222	50.216	47
ED-DE [30]	NA	10012.68	NA	NA	NA
CGA-MU [30]	NA	10143.73	NA	NA	NA
IGA-MU [30]	NA	10042.47	NA	NA	NA
BBO	10098.2810	10058.7303	10066.64044	79.513	40
DE/BBO	10071.8017	10039.4661	10044.6398	72.581	42

**Fig. 4** Convergence characteristic of 160-generators system, obtained by RCCRO, BBO and DE/BBO

algorithms. From the results, it is clear that the performance of the RCCRO algorithm is better, in terms of quality of solutions obtained, compared with many already existing techniques.

4.3.2 Computational efficiency: The time taken by the RCCRO to achieve minimum fuel costs, is quite less compared with that obtained by the BBO, DE/BBO and many other techniques. These are shown in Tables 2, 4, 6

and 8. These results prove significantly better computational efficiency of the RCCRO.

4.3.3 Robustness: Performance of any heuristic algorithms cannot be judged by the results of a single run. Normally, their performance is judged after running the programs of those algorithms for a certain number of trials. Many number of trials should be conducted to obtain a useful conclusion about the performance of the algorithm. An algorithm is said to be robust, if it gives consistent result during these trial runs. Tables 2, 4, 6 and 8 present that out of 50 number of trials for four different test systems, the RCCRO reaches the minimum costs 50, 50, 47 and 47 times, respectively. That means that the efficiency of the RCCRO algorithm to reach minimum solution is 100 and 94%, respectively. On the other hand, BBO, DE/BBO reach the minimum costs (44, 41, 41 and 40) and (46, 45, 43 and 42) times, respectively. Therefore, the performance of the RCCRO is much superior compared with the BBO, DE/BBO and many other algorithms, presented in different literatures.

Therefore, the above results establish the enhanced ability of the RCCRO to achieve superior quality solutions, in a computationally efficient and robust way.

Table 9 Effect of different parameters on performance of RCCRO (minimum fuel cost obtained for test case-4). Bold indicates best result

InitialKE	β	α	MoleColl	KELossRate					
				0.1	0.2	0.5	0.6	0.8	0.9
2000	1000	2000	0.9	10010.3572	10010.1502	10009.8931	10009.8010	10009.7701	10009.7825
1800	900	1500	0.8	10010.1003	10009.9610	10009.7921	10009.7721	10009.7615	10009.7719
1600	800	1300	0.75	10009.9321	10009.8912	10009.7741	10009.7519	10009.7480	10009.7517
1400	700	1000	0.70	10009.8759	10009.8251	10009.7740	10009.7501	10009.7110	10009.7239
1200	600	800	0.60	10009.7952	10009.7710	10009.7574	10009.7228	10009.6921	10009.7014
1000	500	600	0.50	10009.7581	10009.7214	10009.7001	10009.6847	10009.6490	10009.6796
800	400	400	0.40	10009.7040	10009.7001	10009.6820	10009.6551	10009.6312	10009.6427
600	300	300	0.30	10009.6628	10009.6410	10009.6010	10009.5820	10009.5183	10009.5563
400	200	200	0.20	10009.663	10009.6548	10009.6210	10009.5970	10009.5511	10009.5741
200	100	100	0.10	10009.7009	10009.6718	10009.6222	10009.6019	10009.5647	10009.6109

Table 10 Effect of molecular structure size on 160-generators system

Molecular structure size	No. of hits to best solution	Simulation time, s	Max. cost, \$/h	Min. cost, \$/h	Average cost, \$/h
20	23	47.765	10009.6827	10009.5310	10009.6129
50	47	50.216	10009.5827	10009.5183	10009.5222
100	20	53.221	10009.7609	10009.5274	10009.6675
150	12	57.510	10009.9919	10009.5751	10009.8919
200	10	62.982	10010.2527	10009.5962	10010.1214

5 Conclusion

In this paper, a newly developed RCCRO algorithm has been implemented to solve different ELD problems. Different non-linear characteristics of the generator have been included in the ELD problem formulations. The simulation results show that the performance of the RCCRO is better compared with that of several previously developed optimisation techniques. The RCCRO achieves superior quality solutions with high convergence speed in a much robust way. Therefore the RCCRO can be considered as one of the strong tools to solve complex ELD problems. In the future, the RCCRO can also be tried for solution of complex hydrothermal scheduling, dynamic ELD and optimal power flow problems in the search for good characteristics results.

6 References

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