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Optimal power scheduling of thermal units considering emission constraint for GENCOs' profit maximization

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ABSTRACT

In this paper, authors propose a novel method to determine an optimal solution for profit based unit commitment (PBUC) problem considering emission constraint, under a deregulated environment. In a restructured power system, generation companies (GENCOs) schedule their units with the aim of maximizing their own profit by relaxing demand fulfillment constraints without any regard to social benefits. In the new structure, due to strict reflection of power price in market data, this factor should be considered as an important ingredient in decision-making process. In this paper a social-political based optimization algorithm called imperialist competitive algorithm (ICA) in combination with a novel meta-heuristic constraint handling technique is proposed. This method utilizes operation features of PBUC problem and a penalty factor approach to solve an emission constrained PBUC problem in order to maximize GENCOs profit. Effectiveness of presented method for solving non-convex optimization problem of thermal generators scheduling in a day-ahead deregulated electricity market is validated using several test systems consisting 10, 40 and 100 generation units.

Introduction

Along with the development of technological advances throughout the world, structure of different types of industries has been changed dramatically. To this end, power market which is one of the most vital industries has experienced significant changes in its structure. In previous power systems with traditional structure, unit commitment (UC) problem was determination of commitment statuses of thermal generation units so that summation of output power of ON units during certain periods of scheduling periods should meet load demand constraint while cost of operation should be minimized [1].

In order to obtain an optimal solution for nonlinear optimization problem of cost based unit commitment (CBUC), different methods like Lagrangian relaxation (LR) [2], mixed integer programming (MIP) [3], priority list (PL) [4], particle swarm optimization (PSO) [5], genetic algorithm (GA) [6] and imperialist competitive algorithm (ICA) [7] have been employed. These methods are different regarding total economic objective function and optimization techniques.

After deregulation of energy market, the electricity power industry has shifted from a vertically integrated structure to a parallel one. In fact, such the deregulation is decomposition of the vertically integrated power systems to several generating, transmitting and distributing companies. The main aim of this restructuring procedure is to raise a competition among different companies, specifically power generation companies (GENCOs), to provide cheaper as well as top quality choices for electricity customers. Consequently, in the new structure, employed strategies of market should metamorphose. In order to reach such the goal, GENCOs should run a novel profit based unit commitment (PBUC) that is different from traditional UC in terms of objective and demand constraint. In this new defined UC problem, load demand fulfillment is not mandatory anymore and the main purpose of PBUC is to maximize the GENCO's profit in which fuel price, energy selling price and ancillary services are the most highlighted signals for the commitment of thermal units [1].

Recently, numerous techniques have been utilized to reach an optimal solution for nonlinear optimization problem of PBUC under a competitive market. These approaches include: LR [1], Muller method [8], MIP [9], GA [10] and [11], tabu search algorithm (TSA) [12], PSO [13], ant colony optimization (ACO) algorithm [14], artificial bee colony (ABC) algorithm [15], parallel PSO

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Nomenclature

a_i	fuel consumption coefficient of unit i (\$/h)
a_{ei}	emission consumption coefficient of unit i (ton/MW^2 h)
b_i	fuel consumption coefficient of unit i (\$/MW h)
b_{ei}	emission consumption coefficient of unit i (ton/MW h)
c_i	fuel consumption coefficient of unit i (\$/MW^2 h)
c_{ei}	emission consumption coefficient of unit i (ton/h)
$Cost_n$	cost of country n
$C_i(\cdot)$	cost function of unit i (\$), $C_i(P_{(i,t)}) = a_i + b_i \times P_{(i,t)} + c_i \times P_{(i,t)}^2$
$\widehat{C}_i$	cost of imperialist i
$CSC_{(i)}$	cold start-up cost of unit i (\$/h)
$CST_{(i)}$	cooling constant of unit i (h)
DR_i	down ramp rate of unit i (MW/min)
E_{ci}	total mission consumption of unit i (ton/h)
$E_t^{\max}$	maximum allowance of emission at time t
f	objective function
$HSC_{(i)}$	hot start-up cost of unit i (\$/h)
i	index of generator unit
$Ini.\ S_i$	initial state of unit i (h)
$I_{(i,t)}$	commitment state of unit i at time t
N	total number of generating units
$Nd_{(.)}$	number of iterations of main/sub algorithm
N_{col}	number of colonies
N_{imp}	number of imperialists
$Noff_{(i)}^t$	number of continuous OFF states of unit i at transition time
$Non_{(i)}^t$	number of continuous ON states of unit i at transition time
N_p	number of particles (*i.e.* initial solutions) in PSO algorithm
$\widehat{N}_i$	number of initial colonies of imperialist i
$PD_{(t)}$	total system demand at time t (MW)
PF	total profit (\$)
Pos_C^d	positions of a colony at the current decade, in a specific empire
Pos_I^d	positions of an imperialist at the current decade, in a specific empire
Pos_C^{d+1}	positions of a colony at the next decade, in a specific empire
$\widehat{P}_i$	normalized power of imperialist i
$P_{(i)}^{g\max}$	maximum generation of unit i (MW)
$P_{(i)}^{g\min}$	minimum generation of unit i (MW)
$P_{(i,t)}$	generation of unit i at time t (MW)
r_i	a randomly generated numbers in (0, 1)
$R_D(t)$	total reserve at time t
RV	total revenue (\$)
SC_{col}	summation of costs of the colonies, existing in the territory of an empire
$ST_{(i)}$	start-up cost of unit i (\$)
t	index of time
T	dispatch period (h)
TC	total cost (\$)
$T\widehat{P}_i$	total power of imperialist i
$T_{(i)}^{off}$	minimum OFF time of unit i (h)
$T_{(i)}^{on}$	minimum ON time of unit i (h)
UR_i	up ramp rate of unit i (MW/min)
$X_{(i,t)}^{off}$	time duration for which unit i has been OFF at time t (h)
$X_{(i,t)}^{on}$	time duration for which unit i has been ON at time t (h)
β	assimilation weight factor
γ	deviation limit from the original direction
μr_i	prosperity value of ith empire
$\rho_{gm}(t)$	forecasted market price for energy at time t (\$/MW h)
$\hat{\sigma}_i$	probability of imperialist i
ξ	colonies' corporation factor in imperialist' power (*i.e.* a positive number which is considered to be less than 1)

in a shared memory model (PPSO) [16] improved pre-prepared power demand (IPPD) table [17] and parallel nodal ant colony optimization (PNACO) [18] ICA [19] (*i.e.* authors' previous contribution). A glimpse at researches in this area indicates superiority of the Lagrangian based methods. Despite the Lagrangian method enjoys high speed of convergence, LR based methods suffer from getting stuck in the local optimums besides the exponential increase of the problem scale versus increase of the scheduling horizon and number of units. To overcome these obstacles, some hybrid LR-evolutionary methods like combination of GA and LR [20], evolutionary programming (EP) and LR [21], PSO and LR [22], nonlinear programing (NLP) and dynamic programing (DP) [23] an evolutionary method based on priority list [24] are proposed. In [25], uncertainty in loads and availability of the thermal units are considered to solve a UC problem in a competitive market. In [26] an artificial neural network has been employed to model the uncertainty of generation resulted by spinning and non-spinning reserves.

Lately, due to sensitivity of public opinion to the environmental problems and air pollution, more optimal operation of the power generation units are being focused on. To this end, emission as an inseparable ingredient of thermal unit scheduling should be controlled, fuel sources should be exploited as less as possible while GENCOs' profit maximization should be maintained as the final goal. In such situations that several simultaneous objectives are considered, attempting to optimize one of them should not end up to sacrifice of the others. In this paper a compromise is accomplished so that profit of GENCO should be maximized besides maintaining emission table under a certain limit. To this end, Shuffled Frog Leaping Algorithm (SFLA) approach is also utilized to solve PBUC problem with the emission limitation for a case study with ten generation unit [27]. In [28,29] such obligation has been accomplished using PSO and a practical algorithm, respectively. Besides, newfangled heuristic algorithms have attracted considerable attention recently. These algorithms mostly enjoy high potential in terms of convergence speed and solution quality.

In this paper, the authors use a novel evolutionary algorithm which is called ICA to solve the UC problem under a deregulated power market. Considering numerous contributions in case of PBUC problem [20–26], only a small number of researches have been executed PBUC problem considering environmental obligations. To this end, minimization of emission consumption is regarded as the second objective function besides the maximization of GENCO profit. Moreover, a novel meta-heuristic strategy for constraint handling of PBUC problem is formulated in which new penalty factors are determined based on coordination of inherent features of the PBUC problem. As opposed to the traditional constrained handling methods presented in the literature review, this technique provides more optimality and superiority to the other contributions in cases of obtaining quality solutions and convergence speed. In this strategy, a meta-heuristic cascaded ICA–PSO is employed besides the main loop of ICA in order to determine optimal values of penalty factors. Then the optimization problem is solved using the ICA algorithm. By performing the proposed method on the IEEE 39 bus system and for a GENCO consisting of 10 generation units (*i.e.* firstly employed in [27]), validity of the proposed methodology is evaluated. In sum, the main contributions of this paper rather than previously presented methods can be concluded as follows:

- Modification of traditional PBUC problem as a double-objective problem with respect to the recent world's environmental concerns.
- Employing ICA for solving UC problem in restructured energy market.
- Proposing a novel codification for constraint handling of the PBUC problem in order to ameliorate the deficiencies of traditional methods.
- Proposing a cascaded ICA–PSO in order to determine optimal values of penalty factors.

This study is organized in sections as follows:

In first section, a comprehensive literature review on electrical power market and PBUC is presented. In the second section, formulation of PBUC as a complex mixed integer optimization problem is presented. In Section 'Imperialist competitive algorithm', ICA algorithm and fundamental basis of constraint handling are presented. Utilization of a novel meta-heuristic constraint handling for the given problem is discussed, in Section 'Constraint handling'. Finally, implementation of proposed algorithm for several test systems comprising 10 to 100 generating units and simulation results are provided, in Section 'Case study and results'. The paper is concluded in Section 'Conclusion'.

Multi-objective price based unit commitment problem

Along with paralleling and restructuring of electricity markets throughout the world, PBUC problem as one of the most complex and challenging nonlinear optimization problems in market operation has attracted significant concentration. In PBUC, each GENCO tends to schedule their generating units in order to maximize their own profits, regardless of social system welfare [1]. Such the policy is formulated as follows:

Objective function

Mathematical expression of the double objective function of PBUC is formulated as follows [1]:

$$\text{Maximize } PF = RV - TC \tag{1}$$

$$\text{Minimize } E_{ci} = a_{ei} \cdot p_{(i,t)}^2 + b_{ei} \cdot p_{(i,t)} + c_{ei}$$

Or:

$$\text{Minimize } TC - RV \tag{2}$$

$$\text{Minimize } E_{ci} = a_{ei} \cdot p_{(i,t)}^2 + b_{ei} \cdot p_{(i,t)} + c_{ei}$$

Here:

$$RV = \sum_{t=1}^{T}\sum_{i=1}^{N}\left[\rho_{gm}(t) \cdot P_{(i,t)} \cdot I_{(i,t)}\right] \tag{3}$$

$$TC = \sum_{t=1}^{T}\sum_{i=1}^{N}\left[C_i(P_{(i,t)}) + ST_i \cdot I_{(i,t)} \cdot [1 - I_{(i,t-1)}]\right] \tag{4}$$

$$I(i,t) = \begin{cases} 0, & \text{if unit } i \text{ is off} \\ 1, & \text{if unit } i \text{ is on} \end{cases} \tag{5}$$

where start-up cost is defined as follows:

$$ST_{(i,t)} = \begin{cases} \mathrm{CSC}_{(i)}, & \text{if } X_{(i,t)}^{off} \leqslant \mathrm{CST}_{(i)} + T_{(i)}^{off} \\ \mathrm{HSC}_{(i)}, & \text{if } X_{(i,t)}^{off} > \mathrm{CST}_{(i)} + T_{(i)}^{off} \end{cases} \tag{6}$$

The fuel cost function of unit i is defined as follows:

$$C_i(p_{(i,t)}) = a_i + b_i \cdot p_{(i,t)} + c_i \cdot p_{(i,t)}^2 \tag{7}$$

The objective function in (1) is composed of two terms. First term refers to revenue provided by energy provision of thermal units during generation horizon (*i.e.* defined as revenue minus costs) and it should be maximized; while, the second part represents the emission of generating units and should to be minimized.

Constraints

The PBUC is formulated subject to the following system and unit constraints [1].

System constraints

- Demand constraint

$$\sum_{i=1}^{N} P_{(i,t)} \cdot I_{(i,t)} \leqslant P_D(t) \tag{8}$$

- Unit capacity constraint

$$\sum_{i=1}^{N} P_i^{\mathrm{gmax}} \cdot I_{(i,t)} \geqslant P_D(t) + R_D(t) \tag{9}$$

These constraints represent GENCOs' special requirements. For example, a GENCO may have minimum and maximum generation requirements in order to participate in the energy market. Because of reliability requirements, a GENCO may pose lower and upper limits for spinning and no-spinning reserves. In this paper, no reserve consideration is posed to the committed units.

- System emission constraint

Nowadays, due to unprecedented usage of fossil fuels for electrical power generation, dramatic changes have been made in amount of emissions discharged into the atmosphere. Therefore, pollution spread has regarded as a vital challenge in the modern world. Carbon dioxide as one of most destructive products of fossil-fuel combustion (*i.e.* a greenhouse gas) plays a considerable role in global warming. To this end, determining precise generation table of this gas has turned into a necessity to diminish environmental pollutions besides the profit maximization of GENCOs. In this paper, emission of unit i is defined as follows:

$$C_{ei}(p(i,t)) = a_{ei}(p(i,t))^2 + b_{ei}(p(i,t)) + c_{ei} < E_t^{\max} \tag{10}$$

Unit constraints

- Unit generation limits

$$P_{(i)}^{\mathrm{gmin}} \leqslant P_{(i,t)} I_{(i,t)} \leqslant P_{(i)}^{\mathrm{gmax}} \tag{11}$$

- Unit minimum ON/OFF durations

$$\begin{aligned} &\left[X_{(i,t-1)}^{on} - T_{(i)}^{on}\right] * \left[I_{(i,t-1)} - I_{(i,t)}\right] \geqslant 0 \\ &\left[X_{(i,t-1)}^{off} - T_{(i)}^{off}\right] * \left[I_{(i,t)} - I_{(i,t-1)}\right] \geqslant 0 \end{aligned} \tag{12}$$

- Ramp rate

$$P_{i,t-1} - DR_i \leqslant P_{i,t} \leqslant P_{i,t-1} + UR_i \tag{13}$$

Imperialist competitive algorithm

The imperialist competitive algorithm (ICA) is a novel algorithm introduced by Atashpaz Gargari and Lucas in 2007, inspiring a socio-political phenomenon [30]. Then, numerous successful researches have been done using ICA [31]. Like other evolutionary algorithms, this algorithm begins with a primary random population that each of them is called a country. In fact, these countries are random solutions in problem search space. At the beginning of the algorithm's performance, $N_{country}$ initial random countries should be created. Then, costs of initial countries are calculated from (14):

$$Cost_n = f(Conuntry_n) \tag{14}$$

Then, N_{imp} most powerful countries (*i.e.* equivalent to elites in the genetic algorithm) are selected as imperialists. In ICA terminology, these powerful imperialists have the least cost, and other N_{col} countries should be regarded as colonies [30]. At the next stage, colonies should randomly assign to one of the imperialists. During this procedure, number of colonies allocated to each imperialist is proportional to its power. To this end, more powerful imperialist have more opportunity to gain more colonies to satisfy their gluttony. An inverse relation is considered between the cost and power of an imperialist in which the most powerful imperialist has the least cost in order to seize the maximum colonies. Mathematical expression for such a relation is given by (15):

$$\widehat{N}_i = round\{\widehat{P}_i \cdot N_{col}\} \quad i = 1, \ldots, N_{imp} \tag{15}$$

In order to create initial empires, N_i primary colonies should be attributed to the imperialist i. Then, the relative normalized power of each imperialist is calculated by using (16):

$$\widehat{P}_i = \left| \frac{\widehat{C}_i - \max\{\widehat{C}_1, \ldots, \widehat{C}_{N_{imp}}\}}{\sum_{i=1}^{N_{imp}} \widehat{C}_i} \right| \quad i = 1, \ldots, N_{imp} \tag{16}$$

Accordingly, the colonies are divided among the imperialists. Then, imperialists by applying the assimilation policy in terms of different social–political aspects such as language and culture attract colonial countries. This task is modeled by the random movement of each colony toward its relevant imperialist. Fig. 1 shows the scheme of this movement. The new position of the assimilated colony is calculated by (17):

$$Pos_C^{d+1} = Pos_C^d + \beta(Pos_I^d - Pos_C^d) \cdot rand(0,1) \tag{17}$$

In order to improve the search process of algorithm, the colony's movement toward imperialist is executed including a deviation from the original direction. In the procedure of countries' movements during assimilation policy, a colony my gain more power than an imperialist. In this case, the position of the colony and imperialist should be exchanged. In other words, in next steps, all possessions of the previous imperialist will inherit to new more powerful imperialist and they move toward the new imperialist.

After applying the assimilation policy, the revolution operator should be applied in order to prevent algorithm to involve in local optima during the assimilation process. In optimization terminology, the revolution policy has same quality as mutation operator in the genetic algorithm which imposes a sudden change in the structure of colonies. The power of each empire depends on the cost of imperialist and the proportion of colonies' costs that can be calculated by (18):

$$T\widehat{P} = \widehat{C} + \xi \cdot \{mean(SC_{col})\} \tag{18}$$

In each iteration of the algorithm (*i.e.* named decade in ICA), an imperialist competition policy is executed. In this imperialist competition, the imperialist with the least power should lose one of its colonies. In this process, weakest of colony of the weakest empire departs from its empire and joins other empires with certain probabilities. The probability of assigning this colony to each of the empires is also proportional to their power. After several execution of imperialist competition policy during decades, if an imperialist loses all its colonies, it is time for its empire to be collapsed and turns into a colony of other empires. The probability of seizing the weakest colony of weakest empire by each of empires is given by (19):

$$\hat{\sigma}_i = \left| \frac{T\widehat{P}_i - \max\{T\widehat{P}_1, \ldots, T\widehat{P}_{N_{imp}}\}}{\sum_{i=1}^{N_{imp}} T\widehat{P}_i} \right| \quad i = 1, \ldots, N_{imp} \tag{19}$$

The highest chance of seizing the colony of the weakest empire belongs to the empire with the highest level of success. These values are calculated by (20):

$$\begin{aligned} \mu r_i &= \hat{\sigma}_i - r_i, \qquad i = 1, \ldots, N_{imp} \\ &= [\hat{\sigma}_1 - r_1, \hat{\sigma}_2 - r_2, \ldots, \hat{\sigma}_{N_{imp}} - r_{N_{imp}}] \end{aligned} \tag{20}$$

These competitions among the empires leads algorithm to collapse weaker empires and finally, the most powerful imperialist that represents the global optimal solution of the problem remains; while, all the other countries become colonies of this empire. Reaching a certain number of decades or remaining solely one imperialist can be considered as the end criteria of the algorithm. The stop criterion of the algorithm is either to reach the max number of decades or one imperialist remains after the imperialist competition. Fig. 2 shows outline of the presented algorithm.

Constraint handling

In case of numerical optimization and specially regarding nonlinear optimization problems, the previous proposed constraint handling methods can be categorized as follows: use of penalty

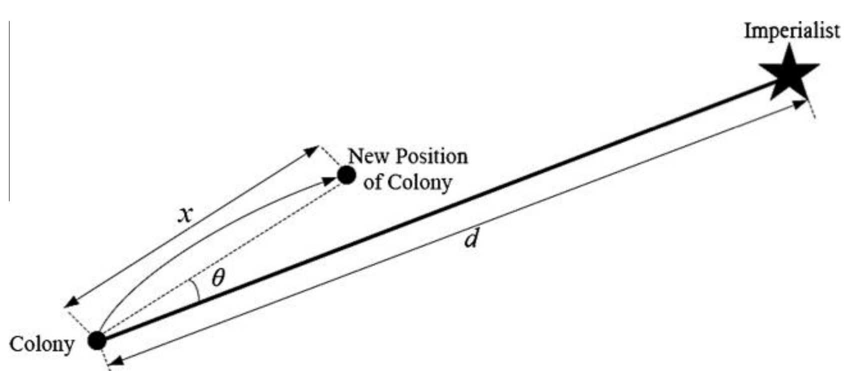

Fig. 1. Assimilation procedure of a colony toward its imperialist.

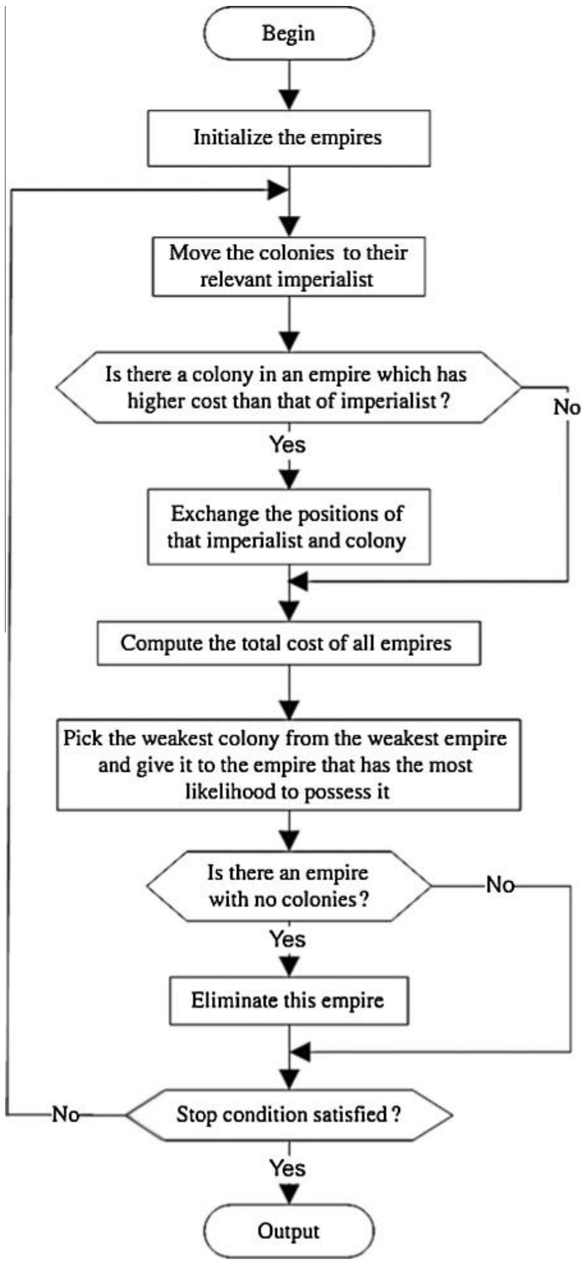

Fig. 2. Outline of the presented ica.

functions, use of certain representations to maintain the population in a feasible search space, decomposition of objectives and constraints and hybrid methods. The most prevalent among the proposed methods (specifically with genetic based algorithms) to overcome constraints complexity (especially inequality constraints) is to utilize penalty costs. To this end, the fundamental approach is to rectify the cost value of country i by extending the domain of cost function $f(X)$ as follows:

$$Cost_i = f(Conuntry_i) \pm \sum_{i=1} V_i Q_i^x \tag{21}$$

In fact, Q_i^x is a cost which penalizes an individual solution and x is the related constrain containing Minimum ON/OFF, demand (Dc), unit reserve (SRc), system emission (SEc) and ramp rate (Rr) constrains. In other word, this additional cost assists an individual solution to assimilate to the feasible solutions. It is assumed that i is feasible then, $Q_i = 0$ which means no penalty is considered for solutions that meet the constraints. The violation values are calculated as follows:

- On/off status violation

If the current status of the unit is OFF and it turns to ON state at the transition time, then:

$$Q_i^{ON/OFF} = \max\left(0, 1 - \frac{Noff_{(i)}^t}{T_{(i)}^{off}}\right) \tag{22}$$

If the current status of unit is ON and it turns to OFF state at the transition time, then:

$$Q_i^{ON/OFF} = \max\left(0, 1 - \frac{Non_{(i)}^t}{T_{(i)}^{on}}\right) \tag{23}$$

- Demand constraint violation

$$Q_i^{Dc} = \max\left(0, \frac{\sum_{i=1}^{N} P_{(i,t)} \cdot I_{(i,t)}}{P_D(t)} - 1\right) \tag{24}$$

- Unit capacity violation

$$Q_i^{Dc} = \max\left(0, 1 - \frac{\sum_{i=1}^{N} P_i^{g\max} \cdot I_{(i,t)}}{P_D(t) + R_D(t)}\right) \tag{25}$$

- System emission violation

$$Q_i^{SEc} = \max\left(0, \frac{C_{ei}(p(i,t))}{E^{\max}} - 1\right) \tag{26}$$

- Ramp rate violation

$$Q_i^{SEc} = \begin{cases} \max\left(0, 1 - \frac{P_{i,t}}{P_{i,t-1} - DR_i}\right) & \text{if unit } i \text{ ramps down} \\ \max\left(0, \frac{P_{i,t}}{P_{i,t-1} + UR_i} - 1\right) & \text{if unit } i \text{ ramps up} \end{cases} \tag{27}$$

In majority of papers, the value of the violation factor (*i.e. Vi* in this research) is considered to be an extremely high value (for instance 10^{12}) and is uniform for all types of violation factor. While, in the case of more complex problems, due to the high sensitivity of the global optimal solution to the initial control parameters of problem, uniform consideration of the violation factor can lead the algorithm to be afflicted with some unfavorable defects such as low speed of convergence and sometimes trapping into local optimums. To overcome such a challenge, the authors have decided to allocate different violation factors to various violations. These values are detailed in Table 1. In order to determine value of violation factors, one of the most routine ways is to run the algorithm for several times with different values and chose the best set of components. However, one of the shortcomings of such the methods is about lack of a certain pattern of varying the parameters.

Despite a good sense of heuristic based algorithms and knowledge of an expert person about PBUC problem, setting limits for these factors is a sort of impossible because of the high sensitivity of algorithm convergence at the ending

Table 1
Values of correction factor for different violations.

Constraint	Ramp rate	ON/OFF	Units capacity	Load-demand	Initial states
Factor $\times 10^{11}$	835	210	10	157	10

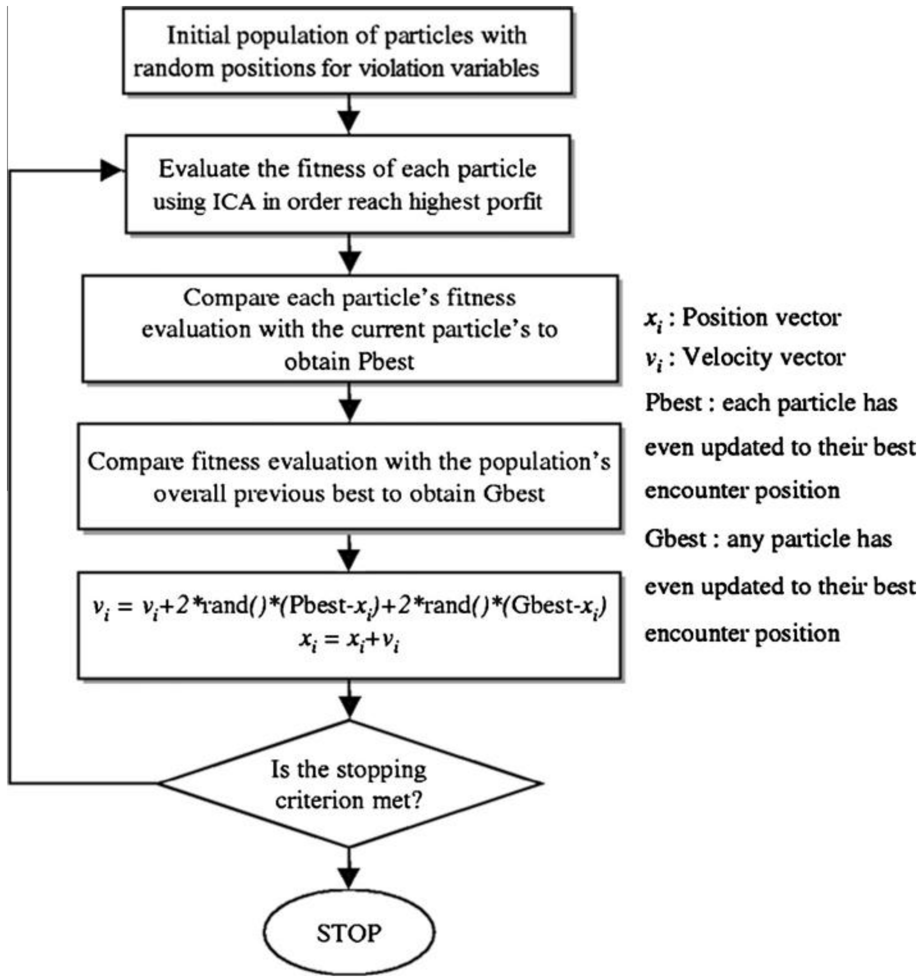

Fig. 3. Outline of the proposed cascaded ICA–PSO.

iterations of algorithms in which level of changing should be infinitesimal. Moreover, due to mixed integer feature of problem, allocating similar factors to constraints that involve to binary variable as well as completely continues constraints can result in low convergence of algorithm. It is noteworthy, at the initial iterations of the algorithm that violations are high, a blind allocation of violation factors does not interfere sudden changes in the optimality of solutions; while, at the ending iterations of the algorithm, a non-compliant violation factor may penalize a competent solution with low rate of violation in a way in which that solution loses its optimality at the next iterations and result in low convergence. An outline for the proposed method of allocation of factors using cascaded ICA–PSO is depicted in Fig. 3.

Due to high speed performance of PSO algorithm authors have utilized this algorithm as a complementary method. Optimum values of coefficients are based on Clerc and Kennedy proposed constriction coefficients for PSO [32]. Coefficients $c1$ (*i.e.* personal learning coefficient) and $c2$ (*i.e.* global learning coefficient) and ω (*i.e.* Inertia weight) are selected as follows:

$$\varphi_1, \varphi_2 > 0 \qquad \varphi = \varphi_1 + \varphi_2 > 4 \tag{28}$$

$$\chi = \frac{2}{\varphi - 2 + \sqrt{\varphi^2 - 4\varphi}} \tag{29}$$

$$\begin{cases} \omega = \chi \\ c_1 = \chi \cdot \varphi_1, \; c_2 = \chi \cdot \varphi_2 \end{cases} \tag{30}$$

For optimum proposed values $\varphi_1 = \varphi_2 = 2.05$, the constriction coefficient χ is 0.7298.

Case study and results

In this research, in order to evaluate quality of solutions, two scenarios comprising *a*) traditional PBUC and *b*) emission constrained PBUC (ECPBUC) are considered. A 24 h scheduling horizon for implementation of UC problem in a competitive environment is considered.

Scenario 1: for first scenario, three GENCOs in scales of small, medium and large are considered as test systems. For this scenario, employing proposed ICA based approach, traditional PBUC without assuming emission constraint is executed.

- *Test system 1*: is a small scale GENCO consists of 10 generating units. Forecasted hourly load demand and energy price in a spot market are detailed in Table 2a [21].

As it can be demonstrated from Table 2a, the daily pattern of load demand experiences two peaks that makes it a challengeable obligation for generation operators to provide an accurate generation table based on the experiences of an expert person. Moreover, the curve of forecasted energy price is shaved coincide with the second peak of load demand at the last hours of the night. Parameters of units are listed in Table 2b [21].

Table 2a
Hourly forecasted load demand and power price in energy market.

Hour (h)	Load (MW)	Price ($/MW)	Hour (h)	Load (MW)	Price ($/MW)
1	700	22.15	13	1400	24.60
2	750	22.00	14	1300	24.50
3	850	23.10	15	1200	22.50
4	950	22.65	16	1050	22.30
5	1000	23.25	17	1000	22.25
6	1100	22.95	18	1100	22.05
7	1150	22.50	19	1200	22.20
8	1200	22.15	20	1400	22.65
9	1300	22.80	21	1300	23.10
10	1400	29.35	22	1100	22.95
11	1450	30.15	23	900	22.75
12	1500	31.65	24	800	22.55

Optimal power scheduling corresponding to the best solution for given 10 unit system is shown in Table 2c.

- *Test system 2*: is a medium scale GENCO consists of 40 generating units. For the 40 generating unit system, the data of 10 generating unit system and the load data are multiplied by 4. Best obtained commitment status for 40 unit system is shown in Table 3a.
- *Test system 3*: is a large scale GENCO consists of 100 generating units. For this system, the data of a10 generating unit system and the load data are multiplied by 10. Best obtained commitment status for 100 unit system is shown in Table 3b.

Comparison of best solutions obtained by proposed method with the other solutions resulted from other contributions, as it can be seen in Table 4, shows superiority of presented technique in case of traditional PBUC.

Scenario 2: for second scenario, all considered assumptions are as same as first scenario while emission constraint is added to traditional PBUC in order to approach reality of power generation systems.

- *Test system 1*: is a small scale GENCO consists of 10 generating units. Emission coefficients of given units are shown in Table 5a. In this test system, hourly emission of GENCO should not exceed 1300 ton/h.

Optimal power schedule corresponding to the best obtained solution for small scale system, resulted by execution of ECPUC using proposed methodology is shown in Table 5b.

As it can be deduced from this table, total number of ON status of units for proposed method is 90 h; while this value for

Table 2b
Data for 10 unit case study.

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
$P_{i\ gmax}$	455	455	130	130	162	80	85	55	55	55
$P_{i\ gmin}$	150	150	20	20	25	20	25	10	10	10
a_i	1000	970	700	680	450	370	480	660	665	670
b_i	16.19	17.26	16.6	16.50	19.70	22.26	27.74	25.92	27.27	27.79
$c_i \times 10^{-2}$	0.048	0.031	0.2	0.211	0.398	0.712	0.079	0.413	0.222	0.173
$T_{i\ off}$	8	8	5	5	6	3	3	1	1	1
$T_{i\ on}$	8	8	5	5	6	3	3	1	1	1
HSC_i	4500	5000	550	560	900	170	260	30	30	30
CSC_i	9000	10,000	1100	1120	1800	340	520	60	60	60
CST_i	5	5	4	4	4	2	2	0	0	0
$Ini.\ S_i$	8	8	−5	−5	−6	−3	−3	−2	−1	−1

Table 2c
Power dispatch and hourly transactions for small scale system (traditional PBUC).

Time (h)	Load (MW)	U1 (MW)	U2 (MW)	U3 (MW)	U4 (MW)	U5 (MW)	U6 (MW)	U7 (MW)	U8 (MW)	U9 (MW)	U10 (MW)	Revenue ($)	Fuel cost ($)	Start-up cost ($)	Profit ($)
1	700	455	245	0	0	0	0	0	0	0	0	15,505	13683.1	0	1821.9
2	750	455	295	0	0	0	0	0	0	0	0	16,500	14554.5	0	1945.5
3	850	455	395	0	0	0	0	0	0	0	0	19,635	16301.9	0	3333.1
4	950	455	455	0	0	0	0	0	0	0	0	20611.5	17353.3	0	3258.2
5	1000	455	455	0	0	0	0	0	0	0	0	21157.5	17353.3	0	3804.2
6	1100	455	455	0	110	0	0	0	0	0	0	23,409	19873.8	1120	2415.2
7	1150	455	455	110	130	0	0	0	0	0	0	25,875	22764.2	1100	2010.8
8	1200	455	455	130	130	0	0	0	0	0	0	25915.5	23105.8	0	2809.7
9	1300	455	455	130	130	130	0	0	0	0	0	29,640	26,184	1800	1656.0
10	1400	455	455	130	130	162	60	0	0	0	0	40855.2	28582.8	340	11932.4
11	1450	455	455	130	130	162	80	0	0	0	0	42571.8	29,048	0	13523.8
12	1500	455	455	130	130	162	60	0	0	0	0	44056.8	28582.8	0	15474.0
13	1400	455	455	130	130	162	0	0	0	0	0	32767.2	26851.6	0	5915.6
14	1300	455	455	130	130	130	0	0	0	0	0	31,850	26,184	0	5666.0
15	1200	455	455	130	110	0	0	0	0	0	0	25,875	22765.6	0	3109.4
16	1050	455	455	110	0	0	0	0	0	0	0	22,746	19903.5	0	2842.5
17	1000	455	455	0	0	0	0	0	0	0	0	20247.5	17353.3	0	2894.2
18	1100	455	455	0	0	0	0	0	0	0	0	20065.5	17353.3	0	2712.2
19	1200	455	455	0	0	0	0	0	0	0	0	20,202	17353.3	0	2848.7
20	1400	455	455	0	0	0	0	0	0	0	0	20611.5	17353.3	0	3258.2
21	1300	455	455	0	0	0	0	0	0	0	0	21,021	17353.3	0	3667.7
22	1100	455	455	0	0	0	0	0	0	0	0	20884.5	17353.3	0	3531.2
23	900	455	445	0	0	0	0	0	0	0	0	20,475	17177.9	0	3297.1
24	700	455	345	0	0	0	0	0	0	0	0	18,040	15427.4	0	2612.6
Total												600517.5	489817.40	4360	106340.1

Table 3a
Commitment statuses and hourly transactions for medium scale system (traditional PBUC).

Time (h)	ON units	Revenue ($)	Cost ($)	Profit ($)	Time (h)	ON units	Revenue ($)	Cost ($)	Profit ($)
1	1–8	62,020	54733.5	7286.5	13	1–20	131068.8	107406.4	23662.4
2	1–8	66,000	58218.8	7781.2	14	1–9, 11–20	127,351	104514.6	22836.4
3	1–8	78,540	65207.6	13332.4	15	1–9, 11–16, 20	106,020	93277.1	12742.9
4	1–8, 14	85390.5	72833.9	12556.6	16	1–8, 13–16	92,768	80855.8	11912.2
5	1–8, 14–15	90,675	75694.5	14980.5	17	1–8, 13, 15–16	93,000	77469.2	15530.8
6	1–8, 10, 13–16	98455.5	85417.6	13037.9	18	1–8, 13, 15–16	88861.5	77995.2	10866.3
7	1–8, 10–16	102,375	90631.2	11743.8	19	1–8, 13, 15–16	89,466	77995.2	11470.8
8	1–8, 10–16	100782.5	89531.2	11251.3	20	1–8, 13, 15–16	91279.5	77995.2	13284.3
9	1–19	117784.8	106910.6	10874.2	21	1–8, 13, 15–16	93,093	77995.2	15097.8
10	1–24	164,360	116652.9	47707.1	22	1–8, 13, 15–16	92488.5	77995.2	14493.3
11	1–24	170287.2	116191.9	54095.3	23	1–8	81,900	68712.0	13188.0
12	1–24	178759.2	116191.9	62567.3	24	1–4, 6–8	71821.75	60525.7	11296.0
Total							2474547.8	2030952.4	443595.4

Table 3b
Commitment statuses and hourly transactions for large scale system (traditional PBUC).

Time (h)	ON units	Revenue ($)	Cost ($)	Profit ($)	Time (h)	ON units	Revenue ($)	Cost ($)	Profit ($)
1	1–20	155,050	136833.9	155,050	13	1–51	329,640	270712.5	329,640
2	1–20	165,000	145547.5	165,000	14	1–42, 45–50	318,402	261024.4	318,402
3	1–20	196,350	163018.9	196,350	15	1–27, 29–41, 45	267,615	235657.5	267,615
4	1–20, 34, 37, 40	214948.5	183795.0	214948.5	16	1–20, 31–40,	231,920	202139.6	231,920
5	1–20, 33–38, 40	232,500	195622.2	232,500	17	1–20, 31–33, 35–36, 38–39	232,500	193382.2	232,500
6	1–20, 25–27, 30–40	250,614	217586.8	250,614	18	1–20, 31–33, 35–36, 38–39	220720.5	193557.6	220720.5
7	1–23, 25–27, 29–40	257,400	227474.0	257,400	19	1–20, 31–33, 35–36, 38–39	222,222	193557.6	222,222
8	1–23, 25–27, 29–40, 43–44	260572.6	234565.7	260572.6	20	1–20, 31–33, 35–36, 38–39	226726.5	193557.6	226726.5
9	1–40, 42–44, 46–50	296308.8	267524.4	296308.8	21	1–20, 31–33, 35–36, 38–39	231,231	193557.6	231,231
10	1–50, 52–60	410,900	290680.6	410,900	22	1–20, 31–33, 35–36, 38–39	229729.5	193557.6	229729.5
11	1–60	425,718	290649.8	425,718	23	1–20	204,750	171780.4	204,750
12	1–60	446,898	290479.8	446,898	24	1–10, 12–19	180,400	152428.5	180,400
Total							6,208,116	5,098,692	1,109,425

Table 4
Comparison of PBUC profit for different methods (scenario 1).

	10 Unit system	40 Unit system	100 Unit system
TS-RP [12]	101,086	–	–
TS-IRP [12]	103,261	–	–
Muller Method [8]	103,296	–	–
ACO [14]	103,890	–	–
PSO [16]	104,365	–	–
PPSO [16]	104,556	–	1,048,083
IPPD [17]	105,164	–	–
Nodal ACO [14]	105,549	–	1,055,392
Parallel ABC [15]	105,878	–	1,056,600
PNACO [18]	105,942	–	1,060,380
ICA	106,340	443,595	1,109,424

Table 5a
Emission coefficients for a 10 Unit system.

Unit no.	a_{ei} (ton/h)	b_{ei} (ton/h)	c_{ei} (ton/h)
1	10.33908	−0.24444	0.00312
2	10.33908	−0.24444	0.00312
3	30.03910	−0.40695	0.00509
4	30.03910	−0.40695	0.00509
5	32.00006	−0.38132	0.00344
6	32.00006	−0.38132	0.00344
7	33.00056	−0.39023	0.00465
8	33.00056	−0.39023	0.00465
9	35.00056	−0.39524	0.00465
10	36.00012	−0.39864	0.0047

traditional and SFLA based scheduling are 87 and 135 h [27]. Although, total operation time of units in ICA based PBUC is approximately equal to that of SLFA, financial and environmental results show an enhancement for proposed method. Needless to say, due to inherent features of PBUC comparing to the traditional UC, such superiority for ICA–PBUC was predictable in terms of profit growth and emission reduction.

Figs. 3a and 3b show comparison of hourly profit and emission of traditional UC with PBUC for the given system using different algorithms.

Fig. 4 shows this comparison among various methods and forecasted demand for the given case study. As it can be seen in these figures, pattern of profit and emission does not follow the variations of load pattern; while such conformity is expectable in the case of UC problems. As stated in literature review, despite numerous contributions in the case of PBUC problem [20–26], only a limited number of papers have been executed a double-objective PBUC problem considering environmental constraints, with the regard to the recent world's environmental concerns.

By referring to Fig. 4 and calculating sum of the generation powers of GENCO during scheduling horizon, total power generated for SFLA–PBUC and ICA–PBUC are 26240 and 26026, respectively. This survey demonstrates superiority of the ICA based PBUC on decrease of employment of facilities that result in higher financial profit and lower deficiency in term of environmental respects.

- *Test system 2*: is a medium scale GENCO as same as test system 2 in scenario 1. For this generating system, emission limit of 10 unit system is multiplied by 4. Optimal commitment of dispatched generating units utilizing proposed methodology for ECPBUC problem in case of given system is depicted in Table 6a.

Table 5b
Power dispatch and hourly transactions for small scale system (ECPBUC).

Time (h)	Load (MW)	U1 (MW)	U2 (MW)	U3 (MW)	U4 (MW)	U5 (MW)	U6 (MW)	U7 (MW)	U8 (MW)	U9 (MW)	U10 (MW)	Revenue ($)	Fuel cost ($)	Start-up cost ($)	Profit ($)	Emission (ton)
1	700	455	245	0	0	0	0	0	0	0	0	15,505	13683.13	0	1821.87	682.77
2	750	455	295	0	0	0	0	0	0	0	0	16,500	14554.50	0	1945.50	754.78
3	850	455	395	0	0	0	0	0	0	0	0	19,635	16301.89	0	3333.11	945.62
4	950	455	455	0	0	0	0	0	0	0	0	20611.5	17353.30	0	3258.20	1090.07
5	1000	455	455	0	0	0	0	0	0	0	0	21157.5	17353.30	0	3804.20	1090.07
6	1100	455	455	0	130	0	0	0	0	0	0	23,868	20213.96	1120	2534.04	1153.23
7	1150	455	455	0	130	0	0	0	0	0	0	23,400	20213.96	0	3186.04	1153.23
8	1200	455	455	0	130	0	0	0	0	0	0	23,036	20213.96	0	2822.04	1153.23
9	1300	455	455	130	130	130	0	0	0	0	0	29,640	26184.02	2900	555.98	1256.95
10	1400	455	455	130	130	162	68	0	0	0	0	41,090	28768.21	340	11981.79	1298.87
11	1450	455	455	130	130	162	80	0	0	0	0	42571.8	29047.98	0	13523.82	1300.40
12	1500	455	455	130	130	162	80	0	0	0	0	44689.8	29047.98	0	15641.82	1300.40
13	1400	455	455	130	130	162	0	0	0	0	0	32767.2	26851.61	0	5915.59	1276.89
14	1300	455	455	130	130	130	0	0	0	0	0	31,850	26184.02	0	5665.98	1256.95
15	1200	455	455	130	130	0	0	0	0	0	0	26,325	23105.76	0	3219.24	1216.39
16	1050	455	335	130	130	0	0	0	0	0	0	23,415	21005.17	0	2409.83	949.94
17	1000	455	285	130	130	0	0	0	0	0	0	22,250	20132.56	0	2117.44	865.45
18	1100	455	385	130	130	0	0	0	0	0	0	24,255	21879.33	0	2375.67	1050.04
19	1200	455	455	130	130	0	0	0	0	0	0	25,974	23105.76	0	2868.24	1216.39
20	1400	455	455	130	130	0	0	0	0	0	0	26500.5	23105.76	0	3394.74	1216.39
21	1300	455	455	130	130	0	0	0	0	0	0	27,027	23105.76	0	3921.24	1216.39
22	1100	455	385	130	130	0	0	0	0	0	0	25,245	21879.33	0	3365.67	1050.04
23	900	455	315	130	0	0	0	0	0	0	0	20,475	17795.28	0	2679.72	851.12
24	700	455	215	130	0	0	0	0	0	0	0	18,040	16052.85	0	1987.15	710.20
Total												625828.3	517139.3	4360	104328.9	26055.8

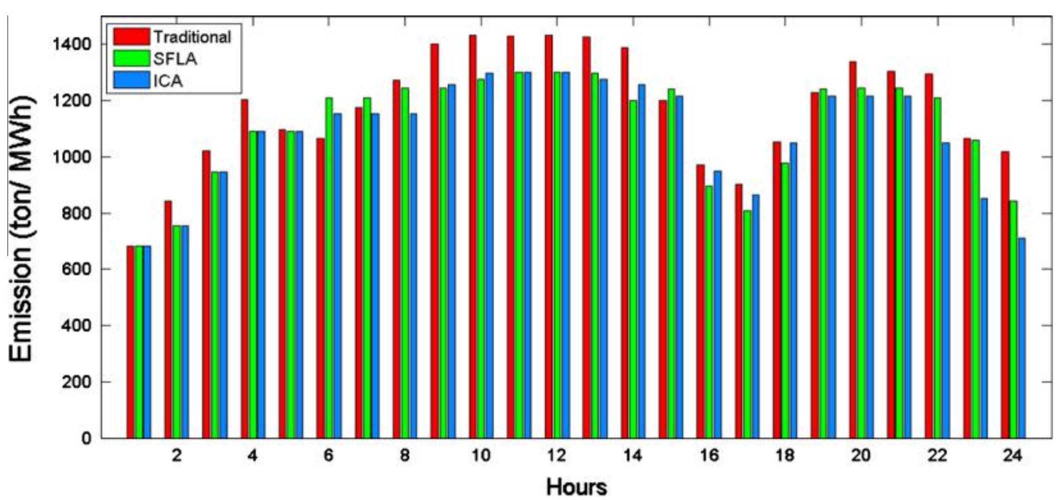

Fig. 3a. Hourly emission versus scheduling horizon for traditional UC, SFLA and ICA–PBUC (scenario 2, test system 1).

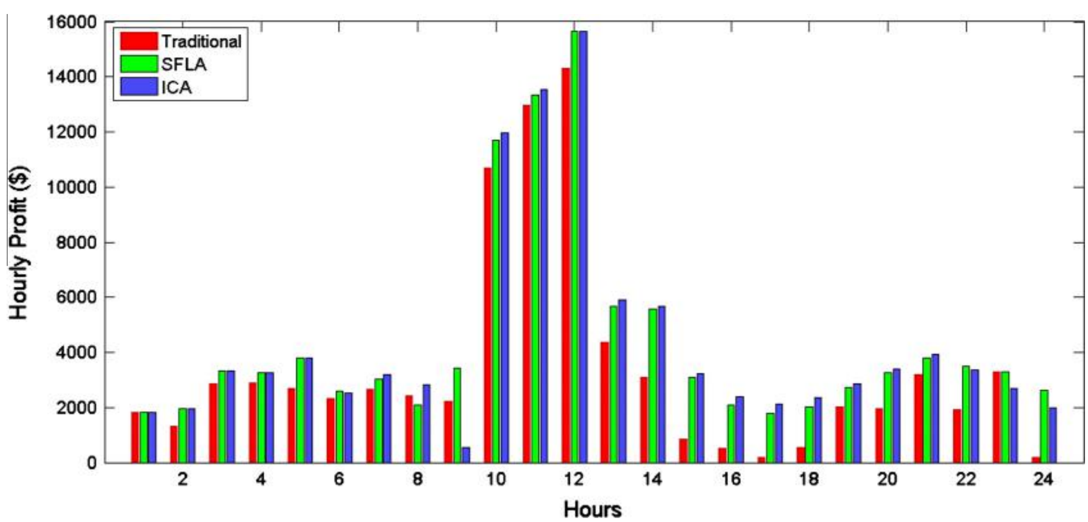

Fig. 3b. Hourly profit versus scheduling horizon for traditional UC, SFLA and ICA–PBUC (scenario 2, test system 1).

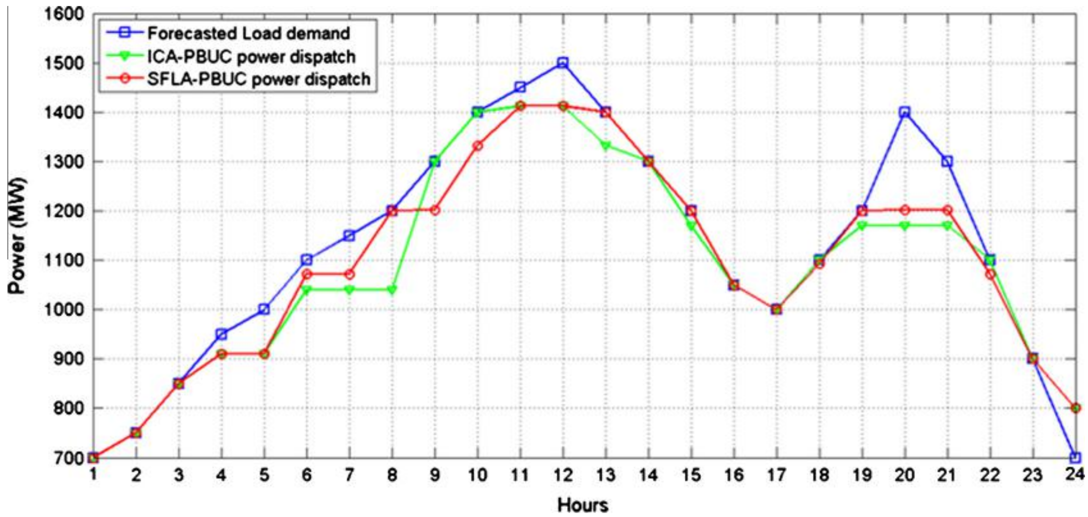

Fig. 4. Comparison of forecasted load demand and dispatched power provided by SFLA and ICA–PBUC (scenario 2, test system 1).

Table 6a
Commitment status and hourly transactions for medium scale system (ECPBUC).

Time (h)	ON units	Revenue ($)	Cost ($)	Profit ($)	Emission (ton)	Time (h)	ON units	Revenue ($)	Cost ($)	Profit ($)	Emission (ton)
1	1–8	62,020	54733.5	7286.5	3607	13	1–20	122840.7	101661.5	21179.3	5200
2	1–8	66,000	58218.8	7781.2	3979.7	14	1–20	122341.4	101661.5	20679.9	5200
3	1–8	78,540	65207.6	13332.4	5013.4	15	1–10, 13–14	89577.4	77837.7	11739.7	5200
4	1–8, 13–14	84647.6	73439.2	11208.5	5200	16	1–10, 13–14	88781.1	77837.7	10943.4	5200
5	1–10, 13–14	92563.3	78937.7	13625.6	5200	17	1–10, 13–14	92563.3	77837.7	14725.6	5200
6	1–10, 13–14	91368.9	77837.7	13531.2	5200	18	1–8, 13–14	82235.7	72148.6	10087.1	5200
7	1–10, 13–14	89577.4	77837.7	11739.7	5200	19	1–8, 13–14	82965.9	72319.2	10646.7	5200
8	1–10, 13–14	87946.8	77600.1	10346.7	5200	20	1–8, 13–14	84647.6	72319.2	12328.5	5200
9	1–10, 13–20	108798.8	101268.6	7530.2	5200	21	1–8, 13–14	86329.4	72319.2	14010.2	5200
10	1–24	155224.6	111793.8	43430.8	5200	22	1–8, 13–14	85768.8	72319.2	13449.6	5200
11	1–24	159455.6	110013.8	49441.8	5200	23	1–8	79470.1	66863.1	12606.9	5200
12	1–24	167388.7	110013.8	57,375	5200	24	1–7	71821.8	60525.7	11,296	4876
Total								2332875.7	1922552.6	410322.5	121476.1

- *Test system 3*: is a large scale GENCO as same as test system 3 in scenario 1. For this generating system, emission limit of 10 unit system is multiplied by 10. Optimal commitment of dispatched generating units utilizing proposed methodology for ECPBUC problem in case of given system is depicted in Table 6b.

Comparison of the best profit obtained by different methods for ECPBUC is shown in Table 7. Results confirm the superiority of proposed methodology compared with the pioneer methods.

Moreover, by comparing results of traditional and emission constrained PBUC (*i.e.* depicted in Tables 4 and 7), it can be inferred

Table 6b
Commitment status and hourly transactions for large scale system (ECPBUC).

Time (h)	ON units	Revenue ($)	Cost ($)	Profit ($)	Emission (ton)	Time (h)	ON units	Revenue ($)	Cost ($)	Profit ($)	Emission (ton)
1	1–20	155,050	136833.9	18216.1	9256.9	13	1–50	303779.6	251844.7	51934.9	13,000
2	1–20	165,000	145547.5	19452.5	10186.0	14	1–50	302544.7	251844.7	50,700	13,000
3	1–20	196,350	163018.9	33331.1	12706.1	15	1–22, 31–32, 35–36	211305.9	182309.9	28,996	13,000
4	1–22, 31–32, 35–36	212714.6	185649.9	27064.7	13,000	16	1–22, 31–32, 35–36	209427.6	182309.9	27117.7	13,000
5	1–22, 31–32, 35–36	218349.4	182309.9	36039.6	13,000	17	1–22, 31–32, 35–36	218349.4	182309.9	36039.6	13,000
6	1–22, 31–32, 35–36	215,532	182309.9	33222.1	13,000	18	1–20, 31–32, 35–36	201274.7	176364.2	24910.5	13,000
7	1–22, 31–32, 35–36	211305.9	182309.9	28,996	13,000	19	1–22, 31–32, 35–36	203073.6	176793.5	26280.1	13,000
8	1–22, 31–32, 35–36	207592.4	181882.2	25710.3	13,000	20	1–22, 31–32, 35–36	207,190	176793.5	30396.5	13,000
9	1–22, 25–26, 31–32, 35–36, 41–50	250330.6	230463.5	19,867	13,000	21	1–22, 31–32, 35–36	211306.3	176793.5	34512.8	13,000
10	1–60	383736.5	280985.2	102751.3	13,000	22	1–22, 31–32, 35–36	209934.2	176793.5	33140.7	13,000
11	1–60	394196.1	272625.2	121570.9	13,000	23	1–22, 31–32	202661.2	171416.1	31245.1	13,000
12	1–60	413807.9	272625.2	141182.7	13,000	24	1–14, 16–17, 19–20	180,400	152428.5	27971.5	12672.4
Total								5685212.6	4674563.1	1010649.7	304821.4

Table 7
Comparison of ECPBUC profit for different methods (scenario 2).

	10 Unit system		40 Unit system		100 Unit system	
	Profit	Emission	Profit	Emission	Profit	Emission
Traditional UC [27]	81,365	28,244	–	–	–	–
PBUC using SFLA [27]	103,262	26,617	–	–	–	–
PBUC using ICA	104,328	26,055	410,322	121,476	1010649.7	304821.4

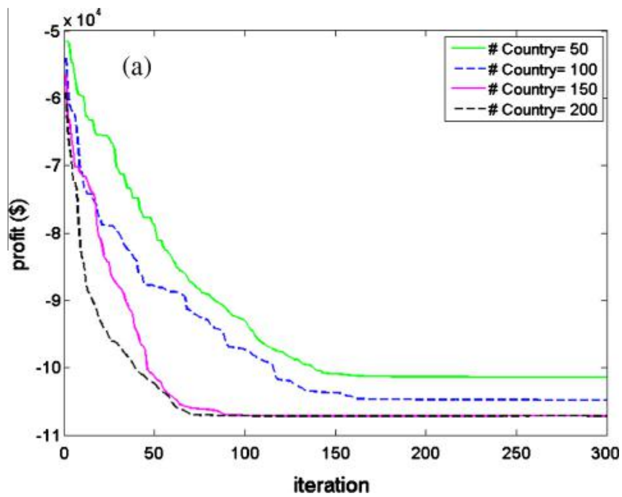

Fig. 5a. Convergence characteristic of the proposed algorithm versus different numbers of initial countries (scenario 2, test system 1).

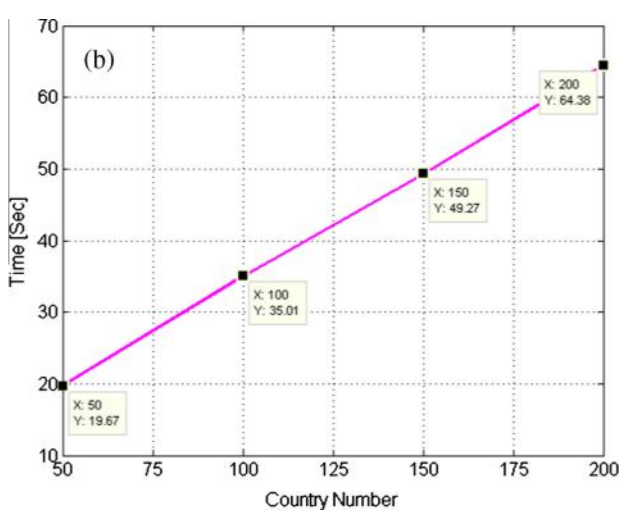

Fig. 5b. Execution time versus population size (scenario 2, test system 1).

that consideration of environmental concerns results in considerable reduction in profit earned for GENCOs. However, with the adoption of Kyoto Protocol which aims to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" as a socialism environmental covenant, this obligation turned into a prominent factor for generation operators.

The ICA algorithm has been implemented in MATLAB 7.6 and their relevant simulations have been run with Intel® Core™ i5-460M Processor (3M Cache, 2.53 GHz) and 4 GB Random Access Memory. Like other evolutionary algorithms, the convergence characteristic of the proposed method depends on the number of primary solutions (*i.e*. number of countries). To this end, algorithm is executed with different numbers of initial countries (*i.e*. 50, 100, 150 and 200 for scenario 2, test system 1). The convergence curves of the algorithm versus different numbers of initial country are shown in Fig. 5a.

Besides, as it can be illustrated from Fig. 5b, execution time varies approximately linearly with the population size increment.

Referring Figs. 5a and 5b, it is deducible that 150 can be an appropriate number for initial population in order to obtain most optimum solution of problem by least possible time. Such the approach is adopted to reach optimal parameters of algorithm in cases of other test systems. Initial values of parameters for proposed main ICA and sub-PSO are obtained through several runs of the algorithm. These values are detailed in Table 8a.

In order to evaluate capability of employing novel meta-heuristic constraint handling proposed, the algorithm is implemented with and without utilizing proposed sub-PSO for scenario 2 – test system 1 for 100 independent runs of program. Results are shown in Table 8b.

For 100 independent runs of traditional and proposed constraint handling technique, these methods have been implemented in order to assess capabilities of the algorithm in terms of quality solution and convergence speed.

As it is illustrated from Table 8c and Fig. 6, results show that employing such an approach can significantly boost the efficiency of the program.

However, results obtained in this work surpass the previous ones, they are not fairly comparable with the all of aforementioned researches implemented by other heuristic algorithms (e.g. TS-RP, PSO, Muller, ACO and ABC) in case of ECPBUC as there are the following differences:

Table 8b
Results of PBUC execution using traditional and proposed constraint handling (scenario 2, test system 1).

	Traditional method	Proposed method
Min	101771.94	102482.21
Mean	102206.56	103808.06
Max	103853.30	104328.92

Table 8a
Optimal parameters of algorithm for proposed methods.

	Nd_{main}	Nd_{sub}	N_p	N_{imp}	N_{col}	β	ζ	γ
10 Unit system	200	100	50	5	145	3	0.02	$(-\pi/4, \pi/4)$
40 Unit system	200	100	100	10	200	3	0.02	$(-\pi/4, \pi/4)$
100 Unit system	200	100	150	10	390	3	0.02	$(-\pi/4, \pi/4)$

Table 8c
Results of PBUC execution with and without adoption of the proposed constraint handling method (scenario 2, test system 1).

	Traditional method (pu)	Proposed method (pu)
Optimality	1	1.0712
Convergence speed	1	0.8900

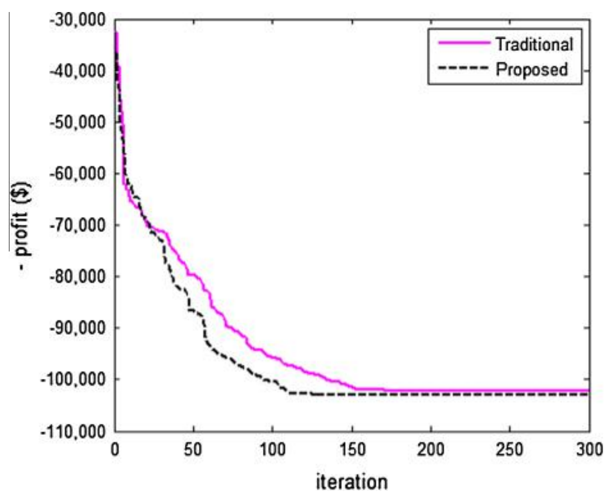

Fig. 6. Convergence performance of PBUC utilizing traditional and proposed method of constraint handling (scenario 2, test system 1).

- The other types of test system are studied.
- In the case of the objective function, another type is considered.
- Data for re-simulation or comparison was not provided.

Conclusion

This paper proposed an advanced evolutionary optimization approach called imperialist competitive algorithm to solve the profit based unit commitment problem under a deregulated environment with emission limitation. A bi-objective function optimization problem formulated in order to maximize generation companies' profit and to minimize emission of thermal units, while all the unit and system constrains should be satisfied. A heuristic penalty factor based approach is utilized to handle the violation of constraints. The presented algorithm has been employed to provide a generation table for a 24 h scheduling horizon. Applicability of the presented method in solving the nonlinear optimization problem of PUBC in a day-ahead deregulated electricity market has been validated using several test systems consisting 10, 40 and 100 generating units. Up to the authors' knowledge, the proposed method surpasses the other previous results.

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