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A New Heuristic Method for Solving Unit Commitment Problem in Competitive Environment

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Abstract— In a restructured power market, traditional scheduling of generating units needs modification. The classical unit commitment problem aims at minimizing the operation costs by satisfying the forecasted electricity load. However, under new structure, Generation companies (GENCOs) schedule their generators with an objective to maximize their own profit by relaxation of the demand fulfillment constraint and without any regard for system social profit, to match the competitive market. A Unit Commitment algorithm with capability of profit maximization plays a significant role in successful development bidding strategies of a competitive generator. In such an environment, power price turns into an important factor in decision process. In this paper the authors utilized a new heuristic technique called Imperialistic Competitive Algorithm (ICA) to exert Profit Based Unit Commitment (PBUC) problem. In fact, the presented approach assists GENCOs to make a decision, how to schedule generators in order to gain the maximum profit by selling adequate amounts of power in power market. The effectiveness of the proposed method to solve generation scheduling optimization problem in a day-ahead deregulated electricity market is validated on 10 generating unit systems available in the literature. Comparison of results obtained from simulation verifies the ability of proposed method.

Index Terms—Deregulation, Electricity Market, Profit Based Unit Commitment, Imperialistic Competitive Algorithm, Competitive Environment.

Nomenclature

a_i	Fuel consumption coefficient of unit *i* (*$/h*)
b_i	Fuel consumption coefficient of unit *i* (*$/MW h*)
c_i	Fuel consumption coefficient of unit *i* (*$/MW^2 h*)
$Cost_n$	Cost of country *n*
C_i	Cost function of unit *i* (*$*), $C_i(P_{(i,t)}) = a_i + b_i * P_{(i,t)} + c_i * P_{(i,t)}^2$
$\hat{C}_i$	Cost of imperialist *i*
$Country_n$	Country *n*
$CSC_{(i)}$	Cold start-up Cost of unit *i* (*$/h*)
$CST_{(i)}$	Cooling constant of unit *i* (*h*)
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
N_{col}	Number of colonies
N_{imp}	Number of imperialists
$\hat{N}_i$	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
$\hat{P}_i$	Normalized power of imperialist *i*
$P_{(i)}^{gmax}$	Maximum generation of unit *i* (*MW*)
$P_{(i)}^{gmin}$	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)
RV	Total revenue (*$*)
SC_{col}	Summation of costs of the colonies, existing in the territory of an empire
$ST_{(i,t)}$	Start-up cost of unit *i* at time t (*$*)
t	Index of time
T	Dispatch period (*h*)
TC	Total cost (*$*)
$T\hat{P}_i$	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*)
$X_{(i,t)}^{off}$	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 *i*th 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)

I. INTRODUCTION

By the advent of technological advances throughout the world, the face of various types of industries has been changed drastically. In this regard, electricity power market as one of the most vital industries has experienced significant changes in its structure.

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During two last decades, because of the economic and environmental restrictions in traditional power plants, usage of Distributed Generations (DGs) has gained a rapid growth. Although, because of some technical and accessibility reasons, many countries all around the world have continued to supply their basic load by means of thermal power plants. Considering that commitment scheduling of the generation units should conform to the load changes and daily load patterns, some of thermal generation units may incur considerable financial losses as the result of adopting an inadequate unit commitment at the off-peak hours of the day which enforces units to operate at less than their nominal capacity. In fact, units scheduling as an inseparable part of research efforts in power generation market is a nonlinear optimization task that plays a considerable role in development of successful techniques of bidding and the day-ahead operation planning for competitive players of the power market. In the previous vertically-integrated power market, the Unit Commitment (UC) was aimed to minimize the production cost (generation costs in addition to start-up costs) by meeting forecasted electricity load and spinning reserve as well as satisfying the operational constrains, such as generators capacity, Up-Down time and ramp rates limitations. In [1]-[8], regarding to the scale of the UC problem, various approaches of providing optimal solution is utilized related to the complexity of the proposed method. These methods can be grouped into two general categories; Lagrangian Relaxation (LR) [1], Branch and Bound (B&B) [2], Mixed Integer Programing (MIP) [3] and Priority List (PL) [4] as classical methods; and Simulated Annealing (SA) [5], Partial Swarm Optimization (PSO) [6], Genetic Algorithm (GA) [7] and Imperialist competitive algorithm (ICA) [8] as heuristic methods.

Recently, by advent of reconstruction in the electric power system, some rules of traditional Unit commitment have been changed [9]. With the enforcement of laws related to restructuring, Generation Companies (GENCOs) solve the UC not for minimizing the total operation cost as before but for maximizing their own profit under deregulated environment that is identified as profit based UC problem (PBUC). PBUC is determined as a method to schedule generators based on economical respects utilizing the forecasted information, such as prices and demand/reserve with an objective to maximize profit of Generation Company that is severely much more challengeable problem to solve than traditional UC.

During recent decade, several classical approaches including LR [10], [11] and MIP [11] methods are employed to solve PBUC problem. However, a glimpse at the researches in this area demonstrates the superiority of Lagrange method, despite the rapid computational process, this method deeply suffers from numerical convergence due to strongly dependence of quality of solutions on the algorithm that updates the Lagrangian multipliers while it is a disease challenge for generation operators to encode the variables [12].

With the formation of evolutionary computation techniques, evolutionary algorithms (e.g. GA [13], Ant Colony Optimization (ACO) [14], Artificial Bee Colony (ABC) [15], Tabu search (TS) [16] and Muller method [17]) and hybrid methods based on combination of the heuristic methods like combination of dynamic programming and nonlinear programming are utilized to solve existing problems. These algorithms do not require derivative information and it is possible to encode the variables so that the optimization will be done with the encoded variables. Moreover, due to ability of heuristic methods to search global optimal solutions and their capability to deal with the complex nonlinear constraints related to the electric power system in terms of generation units scheduling, evolutionary optimization methods acquire much more attention to solve such the problems in the recent years. Despite remarkable time consumption feature of heuristic approaches for computational processes in case of large scale unit commitment problems, in addition to aforementioned advantages, potential of heuristic search algorithms to be used in a high-speed parallel computing technique donates them freedom to overcome large computational time arising from large systems unit commitment. Some of efforts have been reported that authors have contributed the evolutionary methods into LR in order to conquer difficulties related to LR technique. To this end, combination of LR & GA [18], LR & EP [19], LR&PSO [20] are proposed. Regarding to aforementioned literature review, different approaches with the different quality of answers are proposed in recent years.
In this paper, a new method to solve the PBUC optimization problem using a new evolutionary algorithm known as ICA is presented. A mixed integer coding of initial solution, presented in [21], has been employed. System and units constraints like demand constraint, unit generation limits, unit minimum ON/OFF durations are considered. By carrying out the proposed method on two case studies, validation of presented approach is assessed. Then Simulation results are compared with the solutions which provided by the existing methods.

II. IMPERIALISTIC COMPETITIVE ALGORITHM

Imperialist competitive algorithm (ICA) as one of the newfangled global search heuristic algorithms is introduced by Atashpaz Gargari and Lucas based on imperialism and imperialistic competition process [22]. Recently, ICA has been successfully utilized to solve optimization problems [23], [24]. Despite to other heuristic algorithms that use evolution processes of the nature, this algorithm employs a socio-politically inspired strategy to form an optimization frame. To this end, initial solutions that are called countries in ICA are divided to two separate categories based on cost of countries that are results of evaluation of the objective function for given initial countries (1).

$$Cost_n = f\left(Conuntry_n\right) \quad (1)$$

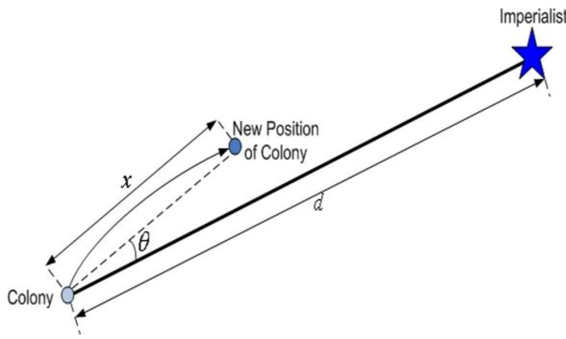

Fig. 1. An illustration of Assimilation operator

In this classification, N_{imp} elite countries are selected as imperialists and N_{col} the rest of countries that are called colonies should accept citizenship of one of the imperialists based on power of them. It is considered that there is an inverse relation between the cost and the power of imperialists in which most powerful imperialist that enjoys least cost value, possess maximum number of colonies. Mathematical expression of this relation is given in (2).

$$\hat{N}_i = round\left\{\hat{P}_i . N_{col}\right\} \qquad i = 1,\dots,N_{imp} \tag{2}$$

To form initial empires, $\hat{N}_i$ number of initial colonies is accrued to the ith imperialist. Then, the normalized power of each imperialist is calculated as follows:

$$\hat{P}_i = \left|\frac{\hat{C}_i - \max\left\{\hat{C}_1,\dots,\hat{C}_{N_{imp}}\right\}}{\sum_{i=1}^{N_{imp}} \hat{C}_i}\right| \qquad i = 1,\dots,N_{imp} \tag{3}$$

After randomly allocation of all colonies to the imperialists, colonies along with their related imperialist establish the empires. At the next step, it is high time colonies moved toward their relevant imperialist with the aim of searching solution surface. Fig. 1 shows assimilation procedure of a colony toward its imperialist.

New position of the assimilated colony can be calculated by (4).

$$Pos_C^{d+1} = Pos_C^d + \beta(Pos_I^d - Pos_C^d).rand(0,1) \tag{4}$$

To enhance the searching process of algorithm, it is considered that movement of colony toward the imperialist is associated with some amount of deviation from the original direction. In addition, a revolution operator is applied to the algorithm after exerting assimilation operator that enforces algorithm to not involve in local optima. As same as mutation operator in GA, this operator executes a sudden surge in the infrastructure of colonies. After implementation of two stated operators, colonies that reach a position better than their relevant imperialists in terms of country cost will conquer position of their imperialists and at the coming decade, other colonies should assimilate toward position of new more powerful imperialist. Then, at the procedure of

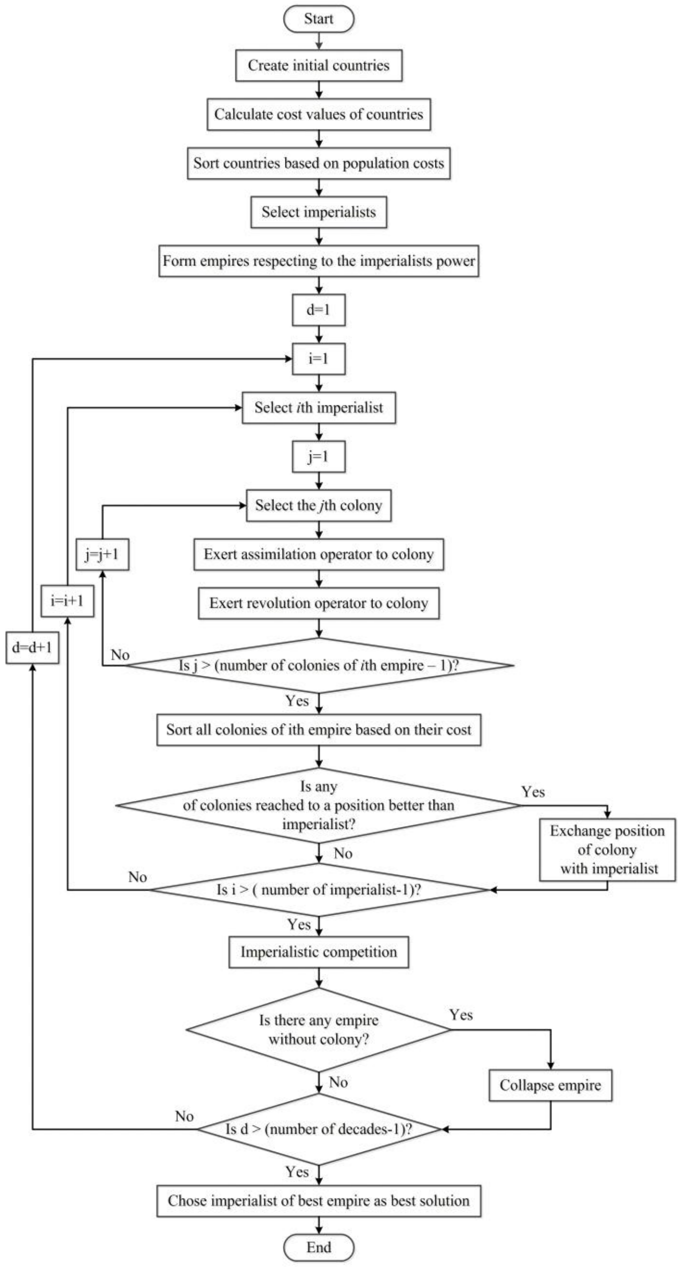

Fig. 2. Outline of the Imperialistic competitive algorithm

imperialistic competition, more powerful empires start to import colonies that are under possession of weaker empires. It is noteworthy to mention that, as it is given in (5), power of each empire depends on the cost of imperialist and a ratio of colonies' costs.

$$T\hat{P} = \hat{C} + \xi.\left\{mean(SC_{col})\right\} \tag{5}$$

The imperialistic competition assists powerful empires to gain more power and leads weaker empires to collapse. In such a manner, most optimal solution (most powerful empire) gains more chance to attract other solution toward a globally optimal solution of the problem. Probability of each empire to possess the weakest colony of the weakest empire is given in (6).

$$\hat{\sigma}_i = \left| \frac{T\hat{P}_i - \max\left\{T\hat{P}_1, ..., T\hat{P}_{N_{imp}}\right\}}{\sum_{i=1}^{N_{imp}} T\hat{P}_i} \right| \qquad i = 1, ..., N_{imp} \tag{6}$$

Highest chance to increase its power by the possessing weakest empire's colony is belonged to the empire that enjoys highest value of prosperity, which is given in (7).

$$\mu r_i = \hat{\sigma}_i - r_i, \qquad i = 1, ..., N_{imp}$$
$$= [\hat{\sigma}_1 - r_1,\ \hat{\sigma}_2 - r_2,\ ...,\ \hat{\sigma}_{N_{imp}} - r_{N_{imp}}] \tag{7}$$

These competitions among the empires leads the algorithm to collapse weaker empires and finally the most powerful imperialist that represents the global optimal solution of problem will stay while all the other countries are colonies of this empire. Fig. 2 shows outline of the presented algorithm.

III. UC PROBLEM FOR COMPETITIVE ENVIRONMENT

In comparison with the cost-based unit commitment in a regulated power industry that aims to satisfy load demand along with the minimizing the operational cost, PBUC problem is one of the most important optimization tasks in a deregulated environment with the aim of maximizing the total profit of GENCOs over the scheduling horizon. In new restructured power market, every GENCO run its own unit commitment by ignoring the load demand restriction to provide results with more profit for its own company. Since, the profit not only depends on cost but on revenue as well, the signal that would enforce a unit to be ON or OFF status would be the energy price, including the fuel purchase price and energy sale [10]. This problem can be formulated mathematically as fallows.

A. Objective Function

The objective function of PBUC problem is given as (8):

$$\text{Maximize } PF = RV - TC \tag{8}$$

Or

$$\text{Minimize } TC - RV \tag{9}$$

Here,

$$TC = \sum_{t=1}^{T}\sum_{i=1}^{N}\left[C_i\left(P_{(i,t)}.I_{(i,t)}\right) + ST_{(i,t)}.I_{(i,t)}.[1 - I_{(i,t-1)}]\right] \tag{10}$$

$$RV = \sum_{t=1}^{T}\sum_{i=1}^{N}\left[\rho_{gm}(t).P_{(i,t)}.I_{(i,t)}\right] \tag{11}$$

Where, start-up cost is defined as follows:

$$ST_{(i,t)} = \begin{cases} CSC_{(i)}, & if\ X_{(i,t)}^{off} \le CST_{(i)} + T_{(i)}^{off} \\ HSC_{(i)}, & if\ X_{(i,t)}^{off} > CST_{(i)} + T_{(i)}^{off} \end{cases} \tag{12}$$

B. Constraints

The PBUC problem is formulated subject to following system and unit constraints.

System Constraints

1. Demand constraint

$$\sum_{i=1}^{N} P_{(i,t)}.I_{(i,t)} \le PD_{(t)} \qquad t = 1, ..., T \tag{13}$$

Unit Constraints

1. Unit Generation Limits

$$P_{(i)}^{gmin} \le P_{(i,t)} I_{(i,t)} \le P_{(i)}^{gmax} \tag{14}$$

2. Unit Minimum ON/OFF Durations

$$\left[X_{(i,t-1)}^{on} - T_{(i)}^{on}\right] * \left[I_{(i,t-1)} - I_{(i,t)}\right] \ge 0 \tag{15}$$

$$\left[X_{(i,t-1)}^{off} - T_{(i)}^{off}\right] * \left[I_{(i,t)} - I_{(i,t-1)}\right] \ge 0 \tag{16}$$

IV. CASE STUDY AND RESULTS

The proposed method for solving PBUC problem is implemented on a 10 generating units- 24 hours test system

TABLE I. DATA FOR THE TEN-UNIT SYSTEM

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

TABLE II. LOAD DEMAND AND FORECASTED PRICE FOR 24 *h*

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
$P_{i\ gmax}$	455	455	130	130	162
$P_{i\ gmin}$	150	150	20	20	25
a_i	1000	970	700	680	450
b_i	16.19	17.26	16.60	16.50	19.70
c_i	0.00048	0.00031	0.002	0.00211	0.00398
$T_{i\ off}$	8	8	5	5	6
$T_{i\ on}$	8	8	5	5	6
HSC_i	4500	5000	550	560	900
CSC_i	9000	10000	1100	1120	1800
CST_i	5	5	4	4	4
$Ini.S_i$	8	8	-5	-5	-6

	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
$P_{i\ gmax}$	80	85	55	55	55
$P_{i\ gmin}$	20	25	10	10	10
a_i	370	480	660	665	670
b_i	22.26	27.74	25.92	27.27	27.79
c_i	0.00712	0.00079	0.00413	0.00222	0.00173
$T_{i\ off}$	3	3	1	1	1
$T_{i\ on}$	3	3	1	1	1
HSC_i	170	260	30	30	30

CSC_i	340	520	60	60	60
CST_i	2	2	0	0	0
$Ini.S_i$	-3	-3	-2	-1	-1

TABLE III. OPTIMAL SOLUTION TO PBUC SCHEDULING PROBLEM

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	15505	13683.13	0	1821.870
2	**750**	455	295	0	0	0	0	0	0	0	0	16500	14554.50	0	1945.500
3	**850**	455	395	0	0	0	0	0	0	0	0	19635	16301.89	0	3333.110
4	**950**	455	455	0	0	0	0	0	0	0	0	20611.5	17353.30	0	3258.200
5	**1000**	455	415	0	130	0	0	0	0	0	0	23250	19512.77	560	3177.230
6	**1100**	455	455	0	130	0	0	0	0	0	0	23868	20213.96	0	3654.040
7	**1150**	455	455	0	130	0	0	0	0	0	0	23400	20213.96	0	3186.040
8	**1200**	455	455	130	130	0	0	0	0	0	0	25915.5	23105.76	1100	1709.740
9	**1300**	455	455	130	130	0	0	0	0	0	0	26676	23105.76	0	3570.240
10	**1400**	455	455	130	130	162	68	0	0	0	0	41090	28768.21	2140	10181.79
11	**1450**	455	455	130	130	162	80	0	0	0	0	42571.8	29047.98	0	13523.82
12	**1500**	455	455	130	130	162	80	0	0	0	0	44689.8	29047.98	0	15641.82
13	**1400**	455	455	130	130	162	0	0	0	0	0	32767.2	26851.61	0	5915.590
14	**1300**	455	455	130	130	130	0	0	0	0	0	31850	26184.02	0	5665.980
15	**1200**	455	455	0	128	162	0	0	0	0	0	27000	23925.72	0	3074.280
16	**1050**	455	455	0	130	0	0	0	0	0	0	23192	20213.96	0	2978.040
17	**1000**	455	415	0	130	0	0	0	0	0	0	22250	19512.77	0	2737.230
18	**1100**	455	455	0	130	0	0	0	0	0	0	22932	20213.96	0	2718.040
19	**1200**	455	455	0	130	0	0	0	0	0	0	23088	20213.96	0	2874.040
20	**1400**	455	455	0	130	0	0	0	0	0	0	23556	20213.96	0	3342.040
21	**1300**	455	455	0	130	0	0	0	0	0	0	24024	20213.96	0	3810.040
22	**1100**	455	455	0	130	0	0	0	0	0	0	23868	20213.96	0	3654.040
23	**900**	455	445	0	0	0	0	0	0	0	0	20475	17177.91	0	3297.090
24	**800**	455	345	0	0	0	0	0	0	0	0	18040	15427.42	0	2612.580
Total												616754.8	505272.4	3800	107682.3

[19]. The data corresponding to this test system consists of system data and generation units' data which are given in Table I and II, respectively. The simulation result obtained using ICA is shown in Table III and this result is compared with that of other approaches in Table IV.

Optimal parameters of ICA for this problem are considered as N_{imp}=5, N_{col}=200, β=5, ζ=0.02 that are obtained through several runs of the program. Parameter γ that tunes the deviation of movement of a colony toward its relevant imperialist from the original direction is set in $(-\pi/4, \pi/4)$. Considering that the parameter γ constraints θ changes, Participation of this parameter into the optimization process assists algorithm to not face with an inaction when imperialists' positions do not experience noticeable changes in the second half of the iterations. As similar to any other heuristic algorithm, convergence of proposed approach depends on the number of initial solutions. To this end, this program has been run with different initial countries of 100, 200, and 300 for several times. Convergence Procedure of the algorithm is depicted in Fig. 3. Result indicates that an initial population equal of 200 can be sufficient to reach an optimal solution.

The proposed heuristic algorithm is implemented on an Intel® Core™ i5-460M processor with 4GB DDR3 Memory.

TABLE IV. COMPARISON OF PBUC SOLUTIONS

Method	Profit [$]
TS-RP [16]	101,086
TS-IRP [16]	103,261
Muller method [17]	103,296
ACO[14]	103,890
Nodal ACO[14]	105,549
Parallel ABC[15]	105,878
ICA	107,682

Execution time of program for this test system is approximately equal to 21 (sec) that is completely acceptable for such a problem with the given dimension of problem. Results obviously demonstrate superiority of the presented ICA in terms of profit and the execution times.

V. CONCLUSION

An efficient approach called imperialistic competitive algorithm (ICA) is proposed in this paper to solve PBUC problem in a restructured power system environment. Based on GENCOs' point of view, a UC problem with the singular aim of maximization of their profits is formulated. Then, the

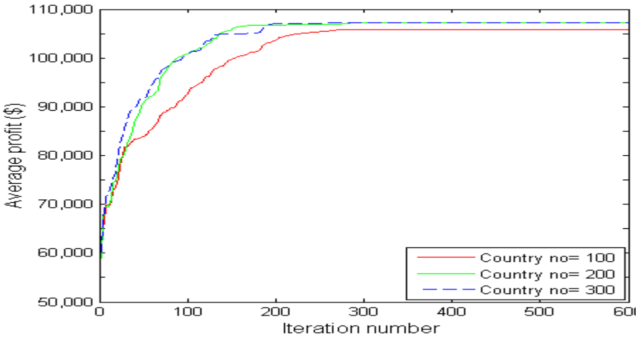

Fig. 3. Convergence characteristics of the Algorithm for different numbers of initial countries (Colony no)

presented algorithm is applied to the 10 generating units, 24 hours test system. An economical scheduling of thermal power plants is prepared by the proposed method. A glimpse at the performance of the ICA based PBUC in comparison with that of existing heuristic methods, demonstrates applicability and high efficiency of the proposed algorithm rather than other algorithm. Moreover, simplicity of the implementation and low time consuming feature of the newfound algorithm remarkably assists generation units' operators to reach an optimal unit commitment in case of larger systems with larger number of generating units.

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