Emission controlled Profit based Unit commitment for GENCOs using MPPD Table with ABC algorithm under Competitive Environment

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Abstract: - The fossil fuelled power plants are discharging green house gases into the atmosphere which leads to the climate change and global warming around the world. Environmental factors become subject of matter for fossil – fuelled power producers and must be considered in the optimization problem. In this article the profit based unit commitment problem has been analyzed with emission limitations using Modified Pre – Prepared power Demand (MPPD) Table with Artificial Bee Colony (ABC) algorithm. An electricity market facilitated by emission minimization is believed to help to reduce the global warming and paves the way to enhance the profit of generation companies. The proposed approach is demonstrated on 10 units 24 hour (IEEE 39 bus system) test systems and numerical results are tabulated. The MPPD-ABC algorithm appears to be robust, simple and reliable optimization algorithm for the solution of PBUC problem with emission constraints.

Key-Words: - Deregulation, Profit based UC, Profit maximization, Emission limitations, MPPD table with ABC algorithm

1 Introduction

Electric power plants consuming coal as primary energy source and releases different types of green house gases such as sulphur oxides, nitrogen oxides and carbon di-oxides into atmosphere. Enormous quantity of these contaminants in atmosphere results to a hazardous impact on mankind. Therefore it is mandatory for electric utilities to minimize the pollution level by reducing SO_2 and NO_2. It is understood that the green house effect can be slowed down only if the emission of CO_2 and other green house gases is reduced drastically [1]. That is why the emission limitation is an important aspect of the electric power plants

A major achievement in this scenario is the Kyoto protocol [2], an international treaty and an agreement under which industrialized countries used to reduce the green house gases by 5% over the five year period of 2008-2012. The novelty of this agreement is that, it prescribes the binding strategies for 37 industrialized countries and the European community for reducing green house gas. Based on this agreement spain and Portugal are permitted to increase this carbon emission up to 15% and 27% respectively in the year 2008-2012. The emission has been increased more than 50% in these countries in 2005. One of the major outcomes of the Kyoto protocol is the establishment of a carbon emissions trading scheme. The emissions trading scheme come into effect from Jan 2005, which includes emissions from plants in the oil refinery, smelting, steel, cement, ceramics, glass, paper mills and permits trading of emission allowances.

The environmental pollution caused by the power generating companies' raise many queries involving environmental safety and methods of minimizing pollution from power plants either by design or by scheduling strategies. Particularly, the prospects of emissions of fossil fuelled power plants which consume coal, oil, gas or combinations as the primary energy source have to be addressed. These emissions can be minimized, either by using the fuel with low emission capacity or by installing post combustion cleaning system. Also proper scheduling of generators helps to reduce the emission of a power plant.

The major part of the work pertaining to emission limitation are concentrated on the economic dispatch problem [3-7] which decides power contribution of each thermal unit, but not deciding on which unit have to be committed for generation at that particular time period. So it becomes significant to have better emission limitation by proper tuning of UC of generating units [8-15]. Most of the literatures, have discussed the impact of emissions on the global warming by analyzing the Economic Dispatch (ED) problem. However after the advent of emission trading allowances, the researchers renewed their ideologies by including the UC problem in emission limitation strategies [16-20].

Recently, the power industry has moved from vertically integrated utilities to one that has been horizontally integrated electric utilities. Restructuring of power systems has resulted in a market based competition by creating an open market competitive environment [21] & [22]. Hence a generation company (GENCO) has the objective to produce and sell the energy with maximum profit. The objective of the UC is not to minimize the generation cost as previously, but to find the schedule that produces maximum profit for the GENCO and it is referred as Profit Based Unit Commitment (PBUC). This profit based UC problem determines how much power and reserve should be offered on a market for achieving maximum profit. The PBUC is a large scale, non convex, non linear, mixed integer optimization problem. It is well known that the electricity markets are highly volatile, the researcher were documented many techniques to solve the PBUC problem. It includes Lagrangian relaxation [21] & [23]. Mixed-integer programming [24–25], Muller method [26-27], Tabu- search [28], Genetic algorithms [29], Memetic algorithm [30], PSO [31], PPSO [32], Nodal ACO [33], Parallel ABC [34] and Hybrid methods such as LR-MIP [35], LR-GA [36] and LR-EP [37-38] have been used for solving the PBUC problems.

Lagrangian relaxation combined with mixed integer programming method has been analyzed by Tao Li and et al. [35]. The solution seems to be better than LR method, but it takes much time for convergence. In reference [39] Mori and Okawa developed and implemented a new hybrid Meta-heuristic based algorithm. Their algorithm was able to solve profit based unit commitment schedule of generating station having nonlinear cost function. An algorithm based on Parallel PSO, Nodal ant colony optimization and parallel ABC was developed by Christopher Colombus et al. for solving the PBUC problem in workstation cluster [32-34]. Chandram and Subramanian [26-27] formed PBUC problem as stochastic optimization problem for a day-ahead energy market and solved by using a new approach with Muller method. Here the problem is analyzed by the proposed method in two stages. Initially, information concerning committed units is obtained by the IPPD table and then the sub-problem of Economic Dispatch (ED) is solved by Muller's method. However, Emission Limitations has not been conceded in this reference.

In recent years, emission limitation has been the subject of intensive researchers. In the era of emission constrained competitive market structure, a GENCO with thermoelectric facilities experiences the optimal tradeoff problem of how to ensure the profit by the management of energy available in fossil fuels for power generation without excessive emission. Since maximizing profit and minimizing emission are conflicting objectives, an innovative approach is need of hour to solve the emission constrained PBUC problem. There are several strategies to reduce gaseous emissions. Out of all, PBUC based emission limitations is the most attractive short term alternatives. Emission constrained PBUC problem solved in the references [40-44]. J. P. S. Catalão et al [40] & [41] was to consider how the emission limitations could be accommodated within PBUC problem. Here an attempt has been made to solve the problem using multi objective approach. Reference [42], investigates the impacts of carbon policies on a GENCO's decision making under multimarket environment. A dynamic decision making model is proposed to deal with the multimarket trading problem for a GENCO during each trading period. Differential Evolution (DE) algorithm is employed to solve the multi-period optimization problem for each time interval. The shuffled Frog Leaping algorithm is proposed to solve the Profit Based Unit Commitment problem under deregulated environment with emission limitation by T. Venkatesan *et al* [43]. The bi-objective optimization problem is formulated to maximize GENCOs profit and minimizing the emission level of thermal units while the prevailing constraints are satisfied.

In this paper, a classic hybrid method is framed by MPPD table with ABC algorithm to solve PBUC with emission limitations. As a first step, the PBUC is formulated by considering emission in the objective function along with standard system constraints. Then MPPD table associated with ABC algorithm is proposed and to derive the solution methodology. Consequently simulation results and comparative studies are made to illustrate the superior performance of the proposed method. Finally relevant conclusions are presented with literature references.

2 Problem Formulation

2.1 The objective function

The objective is to determine the optimal scheduling of thermal generators for maximizing the profit and to minimize the total emission of Generation Companies (GENCOs) subject to standard system constraints. The term profit is defined as the difference between revenue obtained from sale of energy with market price and total operating cost of the generating company.

The PBUC can be mathematically represented by the following equations.

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

$$RV = \sum_{t=1}^{T} \sum_{i=1}^{N} P_{it} FMP_t U_{it} \tag{2}$$

$$TC = \sum_{t=1}^{T} \sum_{i=1}^{N} F(P_{it}) U_{it} + ST.U_{it} \tag{3}$$

The total operating cost, over the entire scheduling period is the sum of production cost and start-up/shutdown cost for all the units. Here, the shutdown cost is considered as equal to zero for all units. The production cost of the committed units is given by the following quadratic equation.

$$Min.F_{it}(P_{it}) = a_i + b_i P_{it} + C_i P_{it}^2 \tag{4}$$

Emission limitation is the most important optimization function in the electrical power system design, operation and scheduling of thermal power plants. There has been a keen attention for emission control over environmental pollution caused by power plants. Thus, the problem of emission of power plants and its influence on the environment, has been analysed by incorporating the emission in the objective function and it is formulated as follows.

$$Emission(EM) = \min \sum_{t=1}^{T} \sum_{i=1}^{N} E(P_{it})\ U_{it} \tag{5}$$

Where

$$E(P_{it}) = \alpha_i + \beta_i P_{it} + \gamma_i P_{it}^2 \tag{6}$$

2.2 Constraints

In this paper power balance, spinning reserve, generator and reserve power limits, minimum ON/OFF time and emission constraints are considered to solve the PBUC problem with emission limitations.

1. Power balance constraint

The system power balance constraint is the most important factor in the PBUC problem. The generated power from all committed units must be less than or equal to the system load demand. Hence, the equation becomes

$$\sum_{i=1}^{N} P_{it} U_{it} \le P_{Dt} \quad 1 \le i \le N \text{ and } 1 \le t \le T \tag{7}$$

2. Spinning reserve constraint

The sum of reserve power of all committed thermal units during the planning period must be less than or equal to total spinning reserve of power plants and it is mathematically defined as

$$\sum_{i=1}^{N} R_{it}\ U_{it} \le SR_t \quad 1 \le i \le N \text{ and } 1 \le t \le T \tag{8}$$

Here, power balance and spinning reserve constraints are different from traditional UC problem because GENCO can now select to produce demand and reserve less than the forecasted level if it creates more profit.

3. Generator and Reserve power limits constraint

The generation limits represent the minimum loading limit below which it is not economical to load the unit, and the maximum loading limit above which the unit should not be loaded. Each unit has generation range. Similarly, the sum of power and reserve power generation of each unit must be less than or equal to maximum generation of that plant, which is represented as:

$$P_{i\min} \le P_i \le P_{i\max} \quad 1 \le i \le N \tag{9}$$

$$0 \le R_i \le P_{i\max} - P_{i\min} \quad 1 \le i \le N \tag{10}$$

$$P_i + R_i \le P_{i\max} \quad 1 \le i \le N \tag{11}$$

4. Minimum up/down time constraints

Once the unit is running, it should not be turned off immediately. Once the unit is de-committed, there is a minimum time before it can be recommitted. These constraints can be represented as

$$Ton_i \geq Tup_i \quad 1 \leq i \leq N \tag{12}$$

$$Toff_i \geq Tdown_i \; 1 \leq i \leq N \tag{13}$$

5. Emission constraint

The sum of emission of all committed thermal units during the planning period must be less than or equal to total emission allowances, which is given by

$$\sum_{t=1}^{T} \sum_{i=1}^{N} E(P_{it})U_{it} \leq EM_t$$

$$1 \leq i \leq N \text{ and } 1 \leq t \leq T \tag{14}$$

3. Proposed methodology

It is experienced from the literatures, that most of the prevailing algorithms have limitations to provide optimal solution. Therefore, this paper is focused to derive a simple approach to improve GENCOs profit under deregulated environment. For this, a table namely Modified Pre-prepared Power Demand (MPPD) table is prepared using the unit data, forecasted price and system demand. The MPPD table identifies the commitment of units and then ABC algorithm is prescribed to solve the fuel cost and revenue function. Remaining part of the article is described as follows.

3.1 Mathematical model of Modified Pre-prepared Power Demand (MPPD) Table

The complete algorithmic steps to prepare the MPPD table are enumerated as follows.

1. The minimum and maximum values of lambda are calculated for all generating units at their minimum and maximum output powers ($P^{\min}(i)$, $P^{\max}(i)$).Therefore two lambda values are possible for each generating units.

The value of lambda (λ) is estimated using the following equations

$$\lambda_{j\min} = \frac{p_{i\min} + \dfrac{b_i}{2c_i}}{\dfrac{1}{2c_i}} \tag{15}$$

$$\lambda_{j\max} = \frac{p_{i\max} + \dfrac{b_i}{2c_i}}{\dfrac{1}{2c_i}} \tag{16}$$

2. The lambda values are arranged in ascending order and label them as λ_j *(where j =1, 2…2N).*

3. The output powers for all generators at each λ_j value are calculated using the formulation

$$p_{ji} = \frac{\lambda - b_i}{2c_i} \tag{17}$$

4. The minimum and maximum output power of generators are fixed as follows.

(i) For minimum output power limit

$$\text{If } \lambda_j < \lambda_{i\min} \text{ then set } p_{ji} = 0 \tag{18}$$

$$\text{If } \lambda_j = \lambda_{i\min} \text{ then set } p_{ji} = p_{i\min} \tag{19}$$

(ii) For maximum output power limit

$$\text{If } \lambda_j > \lambda_{i\max} \text{ then set } p_{ji} = p_{i\max} \tag{20}$$

5. Lambda (λ) value, output powers (P_{ji}) and sum of output powers (SOP) for each λ are listed in the table in ascending order. This table is referred as Modified Pre-prepared Power Demand (MPPD) table.

To illustrate the preparation of MPPD table, a typical 10 unit system is considered and unit data are shown in Table -1.

The ascending order values of lambda are given in Table - 2. Finally the MPPD Table is prepared by applying the above algorithmic steps and shown in Table – 3.

Table 1. Fuel cost and generator limits data for 10 unit system

Unit	a ($)	b ($/MW)	c ($/MW^2)	P_{imin} (MW)	P_{imax} (MW)
1	1000	16.19	0.00048	150	455
2	970	17.26	0.00031	150	455
3	700	16.60	0.00200	20	130
4	680	16.50	0.00211	20	130
5	450	19.70	0.00398	25	162
6	370	22.26	0.00712	20	80
7	480	27.74	0.00079	25	85
8	660	25.92	0.00413	10	55
9	665	27.27	0.00222	10	55
10	670	27.79	0.00173	10	55

Table 2. Values of lambda in ascending order (Ten generating units)

S.No	λ	S.No	λ	S.No	λ	S.No	λ
1	16.33	6	17.12	11	22.54	16	27.51
2	16.58	7	17.35	12	23.48	17	27.78
3	16.63	8	17.54	13	26.00	18	27.82
4	16.68	9	19.90	14	26.37	19	27.87
5	17.05	10	20.99	15	27.31	20	27.98

Table 3. Modified Pre-prepared Power Demand (MPPD) table for 10 units 24 hour systems

S.No	λ ($/MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	SOP (MW)
1	16.33	150	455	0	0	0	0	0	0	0	0	605.00
2	16.58	455	455	0	0	0	0	0	0	0	0	910.00
3	16.63	455	455	0	30.80	0	0	0	0	0	0	940.80
4	16.68	455	455	0	42.65	0	0	0	0	0	0	952.65
5	17.05	455	455	112.5	130	0	0	0	0	0	0	1152.50
6	17.12	455	455	130	130	0	0	0	0	0	0	1170.00
7	17.35	455	455	130	130	0	0	0	0	0	0	1170.00
8	17.54	455	455	130	130	0	0	0	0	0	0	1170.00
9	19.90	455	455	130	130	25.12	0	0	0	0	0	1195.12
10	20.99	455	455	130	130	162	0	0	0	0	0	1332.00
11	22.54	455	455	130	130	162	20	0	0	0	0	1352.00
12	23.48	455	455	130	130	162	80	0	0	0	0	1412.00
13	26.00	455	455	130	130	162	80	0	10	0	0	1422.00
14	26.37	455	455	130	130	162	80	0	54.48	0	0	1466.48
15	27.31	455	455	130	130	162	80	0	55	10	0	1477.00
16	27.51	455	455	130	130	162	80	0	55	54.05	0	1521.05
17	27.78	455	455	130	130	162	80	0	55	55	0	1522.00
18	27.82	455	455	130	130	162	80	50.63	55	55	10	1582.63
19	27.87	455	455	130	130	162	80	82.28	55	55	23.12	1627.40
20	27.98	455	455	130	130	162	80	85	55	55	54.91	1661.91

3.2. Mathematical model of Reduced Modified Pre-prepared Power Demand (RMPPD) table:

The Forecasted energy price plays an important role in preparing the RMPPD table. Because GENCO attains profit only when the forecasted price at the given hour is more than the incremental fuel cost of the generators.

There are two ways to form the RMPPD table from the MPPD table.

1. From the MPPD table, two rows are selected for the predicted power and reserve demand, such that the power demand lies within the limits of Sum of Powers (SOP). The corresponding rows are considered as k and $k+1$..

2. Here, two rows corresponds to the forecasted price are selected from the MPPD table. So that forecasted price falls within the incremental cost. The rows are considered as l and $l+1$.

Therefore, the Reduced Modified Pre-prepared Power Demand (RMPPD) table is formed by

a) If the row $k < l$, then the RMPPD table is formed by considering the option 1.

b) If the row $l < k$, then the RMPPD table is formed by choosing the option 2.

The RMPPD table of 10 unit system for various power demands are developed and shown from Table - 4 to Table – 8.

Table 4. RMPPD Table for Forecasted Demand of 700 MW to 850 MW

λ ($/MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	SOP (MW)
16.33	150	455	0	0	0	0	0	0	0	0	605.00
16.58	455	455	0	0	0	0	0	0	0	0	910.00

Table 5. RMPPD Table for Forecasted Demand of 950 MW to 1150 MW

λ ($/MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	SOP (MW)
16.68	455	455	0	42.65	0	0	0	0	0	0	952.65
17.05	455	455	112.50	130	0	0	0	0	0	0	1152.50

Table 6. RMPPD Table for Forecasted Demand of 1200 MW to 1300 MW

λ ($/MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	SOP (MW)
19.90	455	455	130	130	25.12	0	0	0	0	0	1195.12
20.99	455	455	130	130	162	0	0	0	0	0	1332.00

Table 7. RMPPD Table for Forecasted Demand of 1400 MW

λ ($/MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	SOP (MW)
22.54	455	455	130	130	162	20	0	0	0	0	1352.00
23.48	455	455	130	130	162	80	0	0	0	0	1412.00

Table 8. RMPPD Table for Forecasted Demand of 1500 MW

λ ($/MW)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	SOP (MW)
27.31	455	455	130	130	162	80	0	55	10	0	1477.00
27.51	455	455	130	130	162	80	0	55	54.05	0	1521.05

Now, it is necessary to form the Reduced Committed Units (RCU) table which explains the status of committed units. The RSU table is obtained from RMPPD table by substituting the binary values such a way that if any element in the table is non zero, then it is replaced by 1. Therefore, if binary value is zero, then the corresponding unit is in OFF state. Similarly if binary value is 1, then the unit is in ON state.

For example, the status of generating units for forecasted power demand of 700 MW is as follows

U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}
1	1	0	0	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0	0

The de-commitment of units, Minimum up time and minimum down time constraints are also incorporated in the PBUC problem.

3.3. De-commitment of units

The profit of GENCO depends on the proper scheduling of units. Sometimes, the spinning reserve of the system may increase, due to the large gap between the selected lambda values in the RMPPD table. So, it is important to note that the de-commitment of the unit is necessary to improve the financial benefits of GENCOs. If there is any excessive spinning reserve, the RMPPD table is examined. Then the excessive units in the RMPPD table are de-committed after satisfying the spinning reserve constraints.

3.4. Minimum up time and minimum down time constraints

The OFF time of the unit is less than the minimum down- time, then status of that unit will be OFF. Similarly if ON time of the unit is greater than the up time of the unit, then that unit will be ON. All these useful information are applied in RMPPD table to perform the final unit commitment scheduling.

3.5. ABC Algorithm for solving Economic and Emission Dispatch problem

Artificial Bee Colony (ABC) algorithm has been introduced to solve the Economic and Emission Dispatch(ED) problem so as to determine fuel cost, emission level and revenue function. ABC algorithm is the recently defined algorithms by Dervis Karaboga in 2005, motivated by the intelligent behavior of honey bees [45-46]. It is an optimization tool that provides a population-based search procedure in which individuals called food positions are modified by the artificial bees with time and the bee's aim is to discover the places of food sources with high nectar amount and finally the one with the highest nectar.

In this algorithm, the colony of artificial bees contains three groups of bees: employed bees, onlookers and scouts. The food source represents a possible solution of the optimization problem and the nectar amount of a food source corresponds to the quality (fitness) of the associated solution. Every food source has only one employed bee. Thus, the number of employed bees or the onlooker bees is equal to the number of food sources (solutions).

The onlooker bees evaluate the nectar information and choose a food source depending on the probability value associated with that food source (p_i), calculated by the following expression.

$$p_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n} \tag{21}$$

Where fit_i is the fitness value of the solution i which is proportional to the nectar amount of the food source in the position i and *SN* is the number of food sources is equal to the number of employed bees.

The employed bees exchange their information with the onlookers. In order to produce a candidate food position from the old one, the ABC uses the following expression.

$$V_{ij} = X_{ij} + \phi_{ij}(X_{ij} - X_{kj}) \tag{22}$$

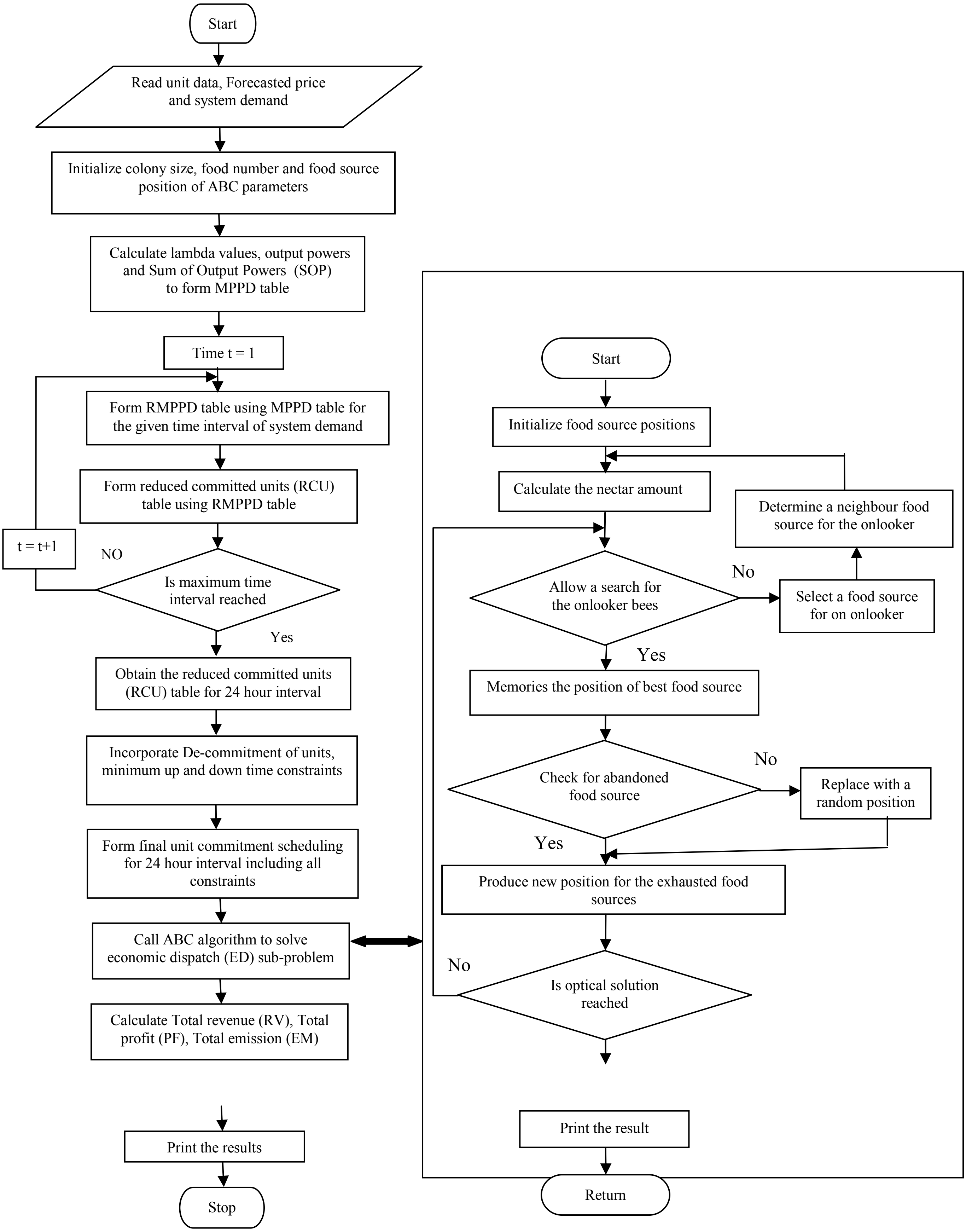

Figure 1. Flow chart for proposed method

Where, $k \in \{1,2.........., BN\}$ and $j \in \{1,2.........., D\}$ are randomly chosen indexes. Although k is determined randomly, it has to be different from *i.* ϕ_{ij} is a random number between [0, 1]. It controls the production of a neighbour food source position around X_{ij} and the modification represents the comparison of the neighbour food positions visually by the bee. If a predetermined number of trials do not improve a solution representing a food source, then that food source is abandoned and the employed bee associated with that food source becomes a scout. The number of trials for releasing a food source is equal to the value of 'limit', which is an important control parameter of ABC algorithm.

The limit value usually varies from $0.001n_eD$ to n_eD. If the abandoned source is X_{ij}, j □ $(1,2,...D)$ then the scout discovers a new food source X_{ij} calculated by the equation.

$$X_{ij} = X_{j\min} + rand(0,1) \times (X_{j\max} - X_{j\min}) \tag{23}$$

Where $X_{j\min}$ and $X_{j\max}$ are the minimum and maximum limits of the parameter to be optimized. There are four control parameters used in ABC algorithm. They are the number of employed bees, number of unemployed or onlooker bees, the limit value and the colony size. Thus, ABC system combines local search carried out by employed and onlooker bees, and global search managed by onlookers and scouts, attempting to balance exploration and exploitation process.

To find the appropriate value of ABC parameters, suitable iterative experiments are performed on the problem. Based on the experimental out come the various parameters are chosen as follows. Colony size = 20; Food number = 10; Food source limit = 100; and maximum number of iterations = 1000**.**

3.6 Implementation of proposed MPPD-ABC algorithm for solving PBUC Problem with emission limitation

The proposed algorithm for solving PBUC problem with emission limitations is summarized as follows.

Step 1 Read unit data (cost coefficients, emission coefficients, generator limits, minimum up/down time limits, startup and shutdown cost) , Forecasted energy price and System demand.

Step 2 Initialize the Artificial Bee Colony (ABC) parameters such as colony size, food number, and food source positions of bees.

Step 3 Calculate the lambda (λ) values, output powers (p_{ji}) and Sum of Output Powers (SOP) to form MPPD Table.

Step 4 From the MPPD Table, evaluate RMPPD Table for the time interval of system demand or forecasted energy price.

Step 5 Form Reduced Committed Units (RCU) Table for a system demand or forecasted energy price using RMPPD table

Step 6 Verify the time interval for 24 hours. If satisfied go to next step otherwise go to step 4.

Step 7 Obtain the reduced committed units (RCU) table for 24 hour interval.

Step8 Incorporate De-commitment of units, minimum up and down time constraints.

Step 9 compute final profit based unit commitment schedule including all constraints.

Step 10 Call ABC algorithm to solve Economic and Emission Dispatch (ED) sub-problem to determine the minimum fuel cost and emission level.

Step11 Evaluate fitness values of objective functions (maximum profit and minimum emission level) of the PBUC problem.

Step 12 If the global optimal solution is reached then the optimization process is terminated or else the procedure is repeated from step 11.

Step 13 Print the simulation results and stop.

4. Numerical results and Discussion

The proposed hybrid mppd-ABC methodology is investigated to illustrate its superior performance on ten units twenty four hour (IEEE 39 bus)**test**

Table 9. Comparison of Unit commitment Schedule of Traditional UC and PBUC (Proposed) for ten unit 24 hour system

Hour (h)	Traditional UC										PBUC (Proposed Method)									
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
2	1	1	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0
3	1	1	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0
4	1	1	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0
5	1	1	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0
6	1	1	1	1	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0	0
7	1	1	1	1	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0
8	1	1	1	1	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0
9	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	0	0	0	0	0
10	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0	0
11	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0	0
12	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	0	0	0
13	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	0	0	0
14	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	0
15	1	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	0	0	0	0
16	1	1	1	1	1	1	0	1	0	0	1	1	1	1	0	0	0	0	0	0
17	1	1	1	1	1	1	0	1	0	0	1	1	0	1	0	0	0	0	0	0
18	1	1	1	1	1	1	0	1	0	0	1	1	0	1	0	0	0	0	0	0
19	1	1	1	1	1	1	0	0	0	0	1	1	0	1	0	0	0	0	0	0
20	1	1	1	1	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0
21	1	1	1	1	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0
22	1	1	0	1	1	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0
23	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
24	1	1	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0

system with cumulative installed power of about 1662 MW. The proposed method is implemented on a computer with a Pentium IV, Intel Dual core 2.2 GHz, 2 GB RAM and simulated in MATLAB 9.1 platform. The simulations were carried out and numerical results are tabulated. This test system is adopted from [43] comprising of 10 generating units with 24 hour scheduling periods and the fuel cost of each generator is estimated by Quadratic equation. The generator data, forecasted system demand, forecasted market price and data for generator emission coefficients are also considered from the same literature and is given in appendix B (Table B1, Table B2 and Table B3).

Table – 9 depicts scheduling of committed units, under traditional UC approach which ensures the equilibrium nature of Generation and Demand. The Table - 9 also provides information for the PBUC in which inequality demand constraint is explained. The power generation pattern for 10 units system is explained in Table 10. The scheduling is designed to maximize the profit and simultaneously minimize the emission level. The results reiterate the fact that only those required generators allowed to dispatch power while the other units remain idle, paving the way to reduce the emission outbursts. Table – 11 describes the simulation results of Fuel cost, Startup cost, Revenue, Profit and Emission of GENCOs and compared with traditional UC. The result of the proposed method (Total profit and emission) is compared with that of existing methods such a traditional UC and SFLA approach and it is displayed in Table -12.

In order to provide more reliable information, Convergence characteristics of best profit for various iterations are displayed in fig. 2. The scheduling pattern of Traditional UC and PBUC is graphically represented in fig. 3.

Table 10. Power Generation of 10 units 24 hour system

h	P_D (MW)	Traditional UC (MW)										PB UC (MW) (Proposed method)									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	700	455	245	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	750	455	275	0	0	0	20	0	0	0	0	455	295	0	0	0	0	0	0	0	0
3	850	455	375	0	0	0	20	0	0	0	0	455	395	0	0	0	0	0	0	0	0
4	950	455	455	0	0	0	40	0	0	0	0	455	455	0	0	0	0	0	0	0	0
5	1000	455	395	130	0	0	20	0	0	0	0	455	455	0	0	0	0	0	0	0	0
6	1100	455	365	130	130	0	20	0	0	0	0	455	455	0	130	0	0	0	0	0	0
7	1150	455	415	130	130	0	20	0	0	0	0	455	455	130	110	0	0	0	0	0	0
8	1200	455	455	130	130	0	30	0	0	0	0	455	455	130	130	0	0	0	0	0	0
9	1300	455	455	130	130	0	80	0	0	0	50	455	455	130	130	130	0	0	0	0	0
10	1400	455	455	130	130	162	58	0	0	0	10	455	455	130	130	162	68	0	0	0	0
11	1450	455	455	130	130	162	80	0	0	0	38	455	455	130	130	162	80	0	0	0	0
12	1500	455	455	130	130	162	80	78	0	0	10	455	455	130	130	162	80	0	0	0	0
13	1400	455	455	130	130	162	33	25	0	0	10	455	455	130	130	162	68	0	0	0	0
14	1300	455	455	130	130	65	20	25	10	0	10	455	455	130	130	130	0	0	0	0	0
15	1200	405	455	130	130	25	20	25	10	0	0	455	455	130	130	0	0	0	0	0	0
16	1050	280	455	130	130	25	20	0	10	0	0	455	335	130	130	0	0	0	0	0	0
17	1000	230	455	130	130	25	20	0	10	0	0	455	415	0	130	0	0	0	0	0	0
18	1100	330	455	130	130	25	20	0	10	0	0	455	455	0	130	0	0	0	0	0	0
19	1200	455	440	130	130	25	20	0	0	0	0	455	455	0	130	0	0	0	0	0	0
20	1400	455	455	130	130	162	0	68	0	0	0	455	455	0	130	0	0	0	0	0	0
21	1300	455	455	130	130	105	0	25	0	0	0	455	455	0	130	0	0	0	0	0	0
22	1100	455	455	0	130	25	0	25	10	0	0	455	455	0	130	0	0	0	0	0	0
23	900	455	455	0	0	0	0	0	0	0	0	455	445	0	0	0	0	0	0	0	0
24	800	305	455	0	0	0	20	0	0	10	10	455	345	0	0	0	0	0	0	0	0

Table 11. Simulation Results for 10 units 24 hour systems

Time (h)	Demand (MW)	Traditional UC (MW)					PBUC (Proposed Method)				
		Fuel cost (Rs)	Start up cost (Rs)	Revenue (Rs)	Profit (Rs)	Emission (tons)	Fuel cost (Rs)	Start up cost (Rs)	Revenue (Rs)	Profit (Rs)	Emission (tons)
1	700	615740.84	0	697725.00	81984.16	682.7662	615740.84	0	697725.00	81984.20	682.766
2	750	676071.62	7650	742500.00	58778.38	841.9329	654952.50	0	742500.00	87547.50	754.814
3	850	754648.37	0	883575.00	128926.63	1020.89	733585.00	0	883575.00	149990.00	945.654
4	950	838129.13	0	968287.50	130158.37	1204.403	780898.50	0	927517.50	146619.00	1090.11
5	1000	900528.20	24750	1046250.00	120971.8	1096.566	780898.50	0	952087.50	171189.00	1090.11
6	1100	1005638.79	25200	1136025.00	105.187	1065.88	908617.45	25200	1074000.00	140242.55	1153.270
7	1150	1045017.84	0	1164375.00	119357.16	1175.338	1068930.67	24750	1164375.00	70694.33	1200.694
8	1200	1086748.50	0	1196100.00	109351.5	1272.043	1087520.77	0	1166197.5	78677.50	1216.420
9	1300	1230342.83	2700	1333800.00	100757.17	1400.717	1038603.80	40500	1200420.00	121316.20	1256.952
10	1400	1326587.15	40500	1849050.00	481962.85	1431.834	1294570.00	7650	1849050.00	546830.00	1298.48
11	1450	1384087.32	0	1967287.50	583200.18	1429.043	1307159.00	0	1915731.00	608522.00	1300.44
12	1500	1468780.98	23400	2136375.01	644194.03	1431.741	1307159.00	0	2011041.00	703882.00	1300.44
13	1400	1353645.46	0	1549800.00	196154.54	1426.691	1294570.00	0	1549800.00	255230.00	1298.78
14	1300	1291851.09	2700	1433250.00	138698.91	1387.083	1177039.94	0	1433250.00	256210.04	1256.952
15	1200	1175951.74	0	1215000.00	39048.26	1200.53	1087520.77	0	1184625.00	97104.23	1216.420
16	1050	1030203.78	0	1053675.00	23471.22	970.7845	967997.15	0	1053600.00	85602.85	926.666
17	1000	993225.48	0	1001250.00	8024.52	903.446	872620.63	0	1001250.00	128629.37	984.631
18	1100	1067290.08	0	1091475.00	24184.92	1053.722	908617.45	0	1031940.00	123322.55	1153.270
19	1200	1107257.96	0	1198800.00	91542.04	1228.534	908617.45	0	1038960.00	130342.55	1153.270
20	1400	1314971.23	23400	1426950.00	88578.77	1336.859	908617.45	0	1066020.00	157402.55	1153.270
21	1300	1207895.94	0	1351350.00	143454.06	1304.426	908617.45	0	1081000.00	172382.55	1153.270
22	1100	1046364.89	2700	1136025.01	86960.12	1295.601	908617.45	0	1074060.00	165442.55	1153.270
23	900	773005.94	0	921375.00	148369.06	1064.438	773005.94	0	921375.00	148369.10	1064.470
24	800	790610.52	13050	811800.00	8139.48	1018.886	694233.9	0	811800.00	117566.10	842.434
Total		25484595.68	166050	29312100.00	3661454.32	28244.15	22,988,712	98,100	27,831,900	4,745,088	26646.85

Table 12. Comparison of total profits and emission of proposed method with the existing methods

Method	Profit (Rs)	Emission (tons)
Traditional UC	3661454.32	28244.15
SFLA	4744910.10	26617.56
MPPD - ABC (Proposed method)	4745088.00	26646.85

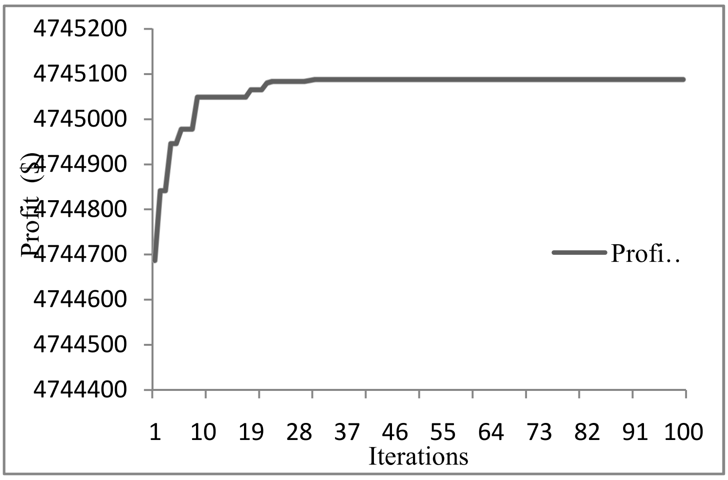

Figure 2. Convergence characteristics of best profit for various iterations

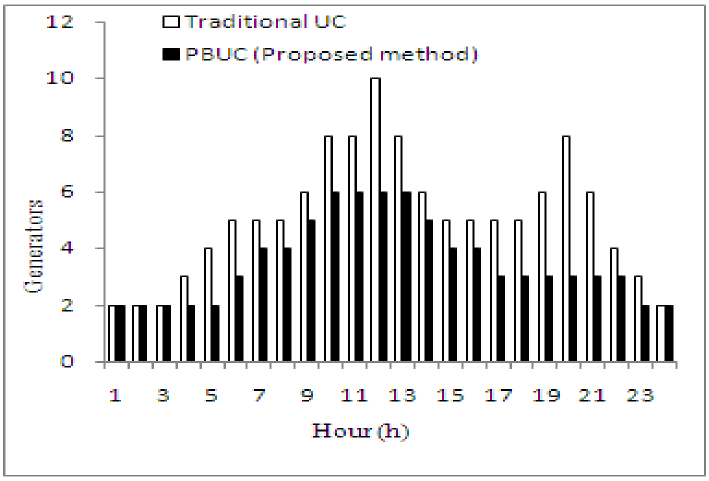

Figure 3. Unit commitment schedule of traditional UC PBUC (Proposed method)

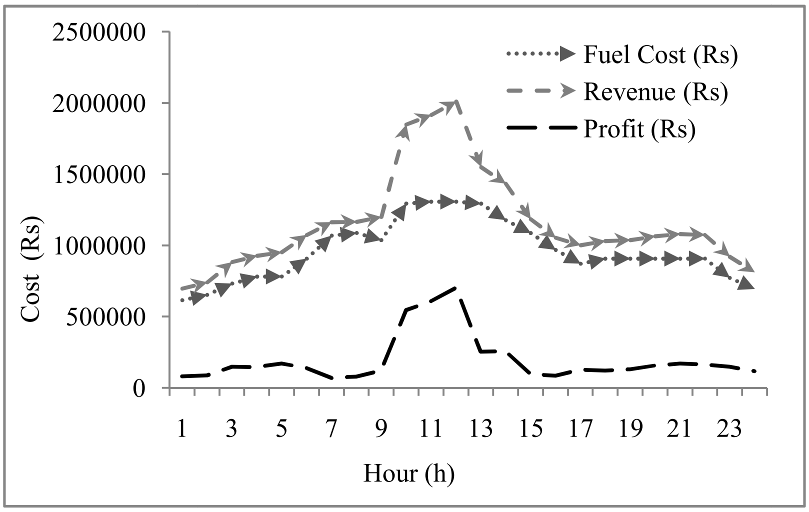

Figure 4. Revenue, Fuel cost and Profit for the ten unit system

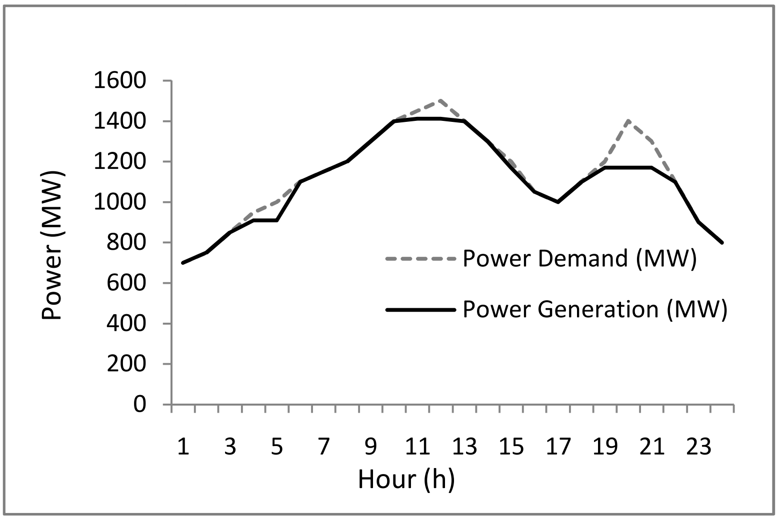

Figure 5. Comparison of power generation and power demand of the ten unit system

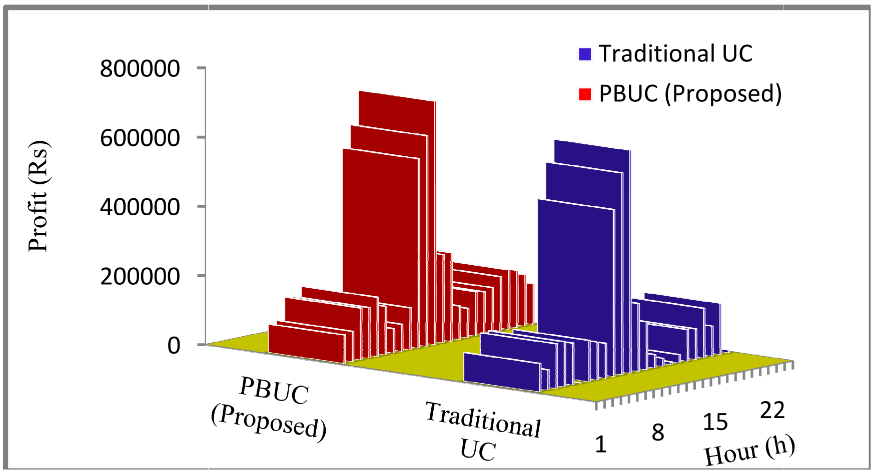

Figure 6. Comparison of profit of Traditional UC and PBUC (Proposed) for ten unit system

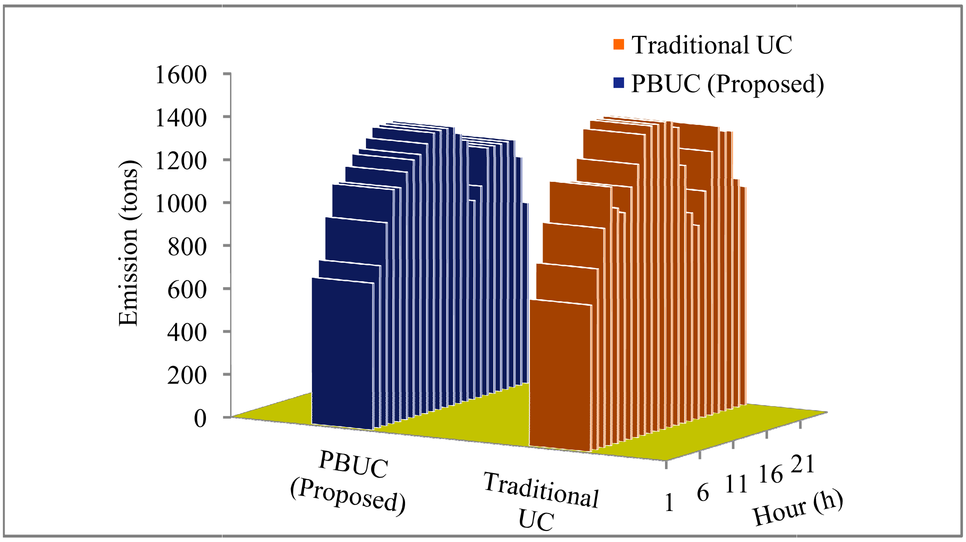

Figure 7.Comparison of Emission level of Traditional UC and PBUC (Proposed) for ten unit system

In fig. 4 Revenue, Total cost and Profit of the GENCOs is reported for each hour of the day-ahead electricity market. The graphical representation of power generation and load demand of referred test system is illustrated in fig. 5. A typical comparison is made for profit of Traditional UC and PBUC (proposed method) is given in fig 6. Finally the emission level of traditional UC and PBUC (proposed method) are compared and are presented in fig. 7. From the results, it is evident that the proposed method improves the profit and minimizes the emission level of the GENCOs than existing methods.

5. Conclusion

In this article, the Emission constrained Profit Based Unit Commitment (PBUC) problem is described under competitive environment. A simple and reliable approach of Modified pre-prepared power demand (MPPD) table with an Artificial Bee Colony (ABC) algorithm is proposed to solve the PBUC problem with emission limitations. The proposed algorithm improves profit and minimizes the emission level by curtailing and scheduling of thermal units in proper manner. To demonstrate the effectiveness and applicability of this method, it has been tested on ten units 24 hour system and numerical results are tabulated. Results are obtained for the optimal profit based unit commitment schedule and MW values for real power, profit and emission of the GENCOs. The experimental result has been compared with Traditional method. From the results, it is observed that the proposed method increases the total profit by 22.85% and minimize the Emission by 5.65% per day when compared with traditional Unit Commitment method. The outcome resulted by the proposed technique ensures the robustness, maximized profit, minimized emission with less computational time over other reported algorithms. Therefore it can be concluded that the proposed MPPD-ABC approach paves the best way for solving the power system optimization problems under deregulated environment.

The technique may be reformulated to include optimization strategies such as

- Security Constrained Unit commitment (SCUC)
- Optimal Bidding strategies (OBS) and Risk constrained OBS problems

To improve the profit of GENCOS

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Appendix A: *Nomenclature*

PF	Total profit of GENCOs

RV	Total revenue of GENCOs
TC	Total generation cost of GENCOs
EM	Total emission of GENCOs
P_{it}	Real power output of i^{th} Generator
P_{Dt}	Forecasted system demand during hour t
P_{it}^{max}	Maximum limit of i^{th} unit during hour of t
P_{it}^{min}	Minimum limit of i^{th} unit during hour of t
FMP_t	Forecasted market price at hour of t
ST	Start up cost
Ton_i	Time duration for which unit i has been ON
$Toff_i$	Time duration for which unit i has been OFF
Tup_i	Minimum up time of unit i
$Tdown_i$	Minimum down time of unit i
N	Number of generating units considered
T	Number of time Periods considered
MPPD	Modified pre-prepared power demand table

RMPPD	Reduced modified pre-prepared power demand table
λ	Incremental cost
N	Number of generating units
UC	Unit commitment
ED	Economic dispatch
PBUC	Profit based unit commitment
a_i, b_i, c_i	Cost co-efficient of i^{th} generator
$\alpha_i, \beta_i, \gamma_i$	Emission co-efficient of i^{th} generator
GENCO	Generation Company
TRANSCO	Transmission Company
DISCO	Distributio0 Company
R_i *(t)*	Reserve of i^{th} generating unit during hour of t
SR *(t)*	Spinning reserve during hour of t
U_{it}	Unit status
PSO	Particle swarm optimization
ACO	Ant colony optimization
NACO	Nodal ant colony optimization
ABC	Artificial bee colony

Appendix B: *Data for 10 Units 24 hour test System*

Table B1 Unit Data for Ten Unit System

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
P_i(max)	455	455	130	130	162	80	85	55	55	55
P_i(min)	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	16.60	16.50	19.70	22.26	27074	25.92	27.27	27.79
C_i	0.00048	0.00031	0.002	0.00211	0.00398	0.00712	0.00079	0.00413	0.00222	0.00173
MU_i	8	8	5	5	6	3	3	1	1	1
MD_i	8	8	5	5	6	3	3	1	1	1
$H_{cost(i)}$	4500	5000	550	560	900	170	260	30	30	30
$C_{cost(i)}$	9000	10,000	1100	1120	1800	340	520	60	60	60
I-State	8	8	-5	-5	-6	-3	-3	-1	-1	-1

Table B2 Forecasted demand and spot price for ten unit 24 hour system

Hour (h)	Forecasted Demand (MW)	Spot price ($/MWh)	Hour (h)	Forecasted Demand (MW)	Spot price ($/MWh)
1	700	996.75	13	1400	1107
2	750	990	14	1300	1102.5
3	850	1039.5	15	1200	1012.5
4	950	1019.25	16	1050	1003.5
5	1000	1046.25	17	1000	1001.25
6	1100	1032.75	18	1100	992.25
7	1150	1012.5	19	1200	999
8	1200	996.75	20	1400	1019.25
9	1300	1026	21	1300	1039.5
10	1400	1320.75	22	1100	1032.75
11	1450	1356.75	23	900	1023.75
12	1500	1424.25	24	800	1014.75

Table B3. Data for generator emission coefficients

Units	α_i(ton/h)	β_i(ton/MW h)	γ_i(ton/MW^2 h)
U1	10.33908	-0.24444	0.00312
U2	10.33908	-0.24444	0.00312
U3	30.03910	-0.40695	0.00509
U4	30.03910	-0.40695	0.00509
U5	32.00006	-0.38132	0.00344
U6	32.00006	-0.38132	0.00344
U7	33.00056	-0.39023	0.00465
U8	33.00056	-0.39023	0.00465
U9	33.00056	-0.39524	0.00465
U10	36.00012	-0.39864	0.00470

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