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Unit Commitment by a Fast and New Analytical Non-iterative Method Using IPPD Table and "λ-logic" Algorithm

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Abstract- *Many different methods have been presented to solve unit commitment (UC) problem in literature with different advantages and disadvantages. The need for multiple runs, huge computational burden and time, and poor convergence are some of the disadvantages, where are especially considerable in large scale systems. In this paper, a new analytical and non-iterative method is presented to solve UC problem. In the proposed method, improved pre-prepared power demand (IPPD) table is used to solve UC problem, and then analytical "λ-logic" algorithm is used to solve economic dispatch (ED) sub-problem. The analytical and non-iterative nature of the mentioned methods results in simplification of the UC problem solution. Obtaining minimum cost in very small time with only one run is the major advantage of the proposed method. The proposed method has been tested on 10 unit and 40-100 unit systems with consideration of different constraints, such as: power generation limit of units, reserve constraints, minimum up and down times of generating units. Comparing the simulation results of the proposed method with other methods in literature shows that in large scale systems, the proposed method achieves minimum operational cost within minimum computational time.*

Keyword: Unit commitment, Economic dispatch, IPPD table, λ-logic algorithm.

NOMENCLATURE

a_i, b_i, c_i	Fuel cost coefficients of unit '*i*'
$Cost_{index,i}$	Cost index of unit '*i*'
CSU_i	Cold start-up cost of unit '*i*'
F	Total fuel cost
$F_{fuel,t}$	Total fuel cost at time '*t*'
$F_i(p_{i,t})$	Fuel cost of unit '*i*' at time '*t*'
HSU_i	Hot start-up cost of unit '*i*'
N	Number of units
N_t	Number of on-line units at time '*t*'
$P_{i,average}$	Average power of unit '*i*'
$p_{i,\max}$	Maximum power of unit '*i*'
$p_{i,\min}$	Minimum power of unit '*i*'
$p_{i,t}$	Power of unit '*i*' at time '*t*'
PD_t	Power demand at time '*t*'
PPD_j	Power demand data corresponding to λ_j
R_t	Required reserve at time '*t*'
SD_i	Shut-down cost of unit '*i*'
SU_i	Start-up cost of unit '*i*'
T	Number of hours
$T_{i,cold}$	Cold start hours of unit '*i*'
$T_{i,down}$	Minimum down time of unit '*i*'
$T_{i,off}$	Continuous "off" time duration of unit '*i*'
$T_{i,on}$	Continuous "on" time duration of unit '*i*'
$T_{i,up}$	Minimum up time of unit '*i*'
$U_{i,t}$	Status of unit '*i*' at time '*t*'
$\lambda_{i,\max}$	Maximum incremental fuel cost of unit '*i*'
$\lambda_{i,\min}$	Minimum incremental fuel cost of unit '*i*'
λ_j	Incremental fuel cost of unit '*j*'
$\lambda_{j,t}$	Incremental fuel cost of unit '*j*' at time '*t*'
$\lambda_{PD,t}$	Incremental fuel cost corresponding to power demand at time '*t*'

1. INTRODUCTION

Determination of "on" and "off" states of generating units is defined as unit commitment (UC) problem [1]. The scheduling of generating units to supply predicted power demand with minimum operational cost is the purpose of UC problem. This schedule have to satisfy different constraints such as generator power limits, spinning reserve, and minimum up and down times of units. After determination of the committed units, economic dispatch (ED) sub-problem should be solved. ED sub-problem is solved to specify optimal generation of each on-line unit to reach minimum operational cost [2-4].

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Existing solutions for UC problem in literature can be classified into three categories, as: (a) classical methods, (b) heuristic and intelligent methods, and (c) hybrid methods. Classical methods such as Priority List (PL) [5, 6], Dynamic Programming (DP) in Ref. [7], Branch-Bound in Ref. [8], Mixed Integer Programming (MIP) [9-11], Mixed Integer Linear Programming (MILP) in Ref. [12] and Lagrangian Relaxation (LR) [13-15] present a simple solution for UC problem. However, most of them suffer from major drawbacks, such as poor convergence, rough quality and inconsistent results, and big computational time in large scale systems [16, 17].

In order to have a better solution, heuristic and intelligent methods have been used for solving UC problem, such as: Hopfield Neural Network (HNN) [18, 19], Genetic Algorithm (GA) [20, 21], Simulated Annealing [22, 23], Binary Grey Wolf Optimizer (BGWO) [24, 25], Evolutionary Programming (EP) [26-28], Particle Swarm Optimization (PSO) [29-31], Ant Colony Search Algorithm (ACSA) in Ref. [32], Tabu Search Algorithm (TSA) in Ref. [33], Binary Quantum Search Algorithm in Ref. [34], Binary Coded Modified Moth Flame Optimization Algorithm (BMMFOA) in Ref. [35], Ordinal Optimization Theory in Ref. [36], Binary Whale Optimization Algorithm in Ref. [37]. These methods can obtain a near global optimum [38, 39]. However, because of their iterative nature, considerable computational time and space are required in large scale systems [39, 40].

To reduce disadvantages of single methods in large scale systems, hybrid methods such as Lagrangian Relaxation and Genetic Algorithm (LRGA) in Ref. [41], Lagrangian Relaxation and Particle Swarm Optimization (LRPSO) in Ref. [42], Dynamic Programing, Genetic Algorithm and Particle Swarm Optimization (DP–GA–PSO) [43], Genetic Algorithm and Fuzzy Logic in Ref. [44], Evolutionary Programming with Tabu Search Algorithm (EP–TSA) [45] and LR–EP [46, 47], Tabu Search and Artificial Bee Colony Algorithm (TS–ABCA) [48], Particle Swarm Optimization and Grey Wolf Optimizer (PSO–GWO) in Ref. [49], Binary Particle Swarm Optimization, Differential Evolution Algorithm and Lambda Iteration Method in Ref. [50], Genetic Algorithm and Mixed Integer Linear Programming [51], Binary Successive Approach and Civilized Swarm Optimization (BSA-CSO) in Ref. [52], and Particle Swarm Optimization and Firefly Algorithm (PSO-FA) in Ref. [53] have been employed for solving UC problem. Hybrid methods are more effective than single methods due to reduced computational time and less operational cost [40].

However, the main problem of heuristic search techniques (single and hybrid) is that there is no guarantee to find an optimal solution in one run [54]. Therefore, to reach an optimal solution it is required to have multiple runs.

To cancel the need for multiple runs, [55] offers improved pre-prepared power demand (IPPD) table method to solve UC problem. This table could be prepared using fuel cost coefficients of generators and their output power limits. IPPD table is a simple, efficient and non-iterative way to find committed units in a specified power demand. However, using Muller Root Finding method to solve ED sub-problem by [55] leads to decrease the advantages of IPPD table method. This is because of iterative and time consuming nature of Muller method. More details of different methods for UC problem are summarized in [56-58].

In this paper, an analytical method is proposed based on the IPPD table and "λ-logic" algorithm [59]. "λ-logic" algorithm is a simple and non-iterative approach, which uses pre-prepared power demand data (PPD) to solve ED problem. Implementation of these two analytical, non-iterative and efficient methods in unit commitment problem results in time saving and solution simplicity, especially in large scale systems. In addition, the proposed method do not need multiple runs to reach optimum solution, because the analytical nature of the proposed method guarantees its unique response. The proposed method is tested on 10 unit and 40-100 unit systems. The simulation results show that the proposed method can be a suitable choice for large scale systems, because of its time and cost saving benefits.

2. UNIT COMMITMENT PROBLEM

2.1. Identification of UC problem

In unit commitment problem, state of generating units is determined to minimize the total cost of the system and to satisfy all constraints for a predicted load demand. The objective function of UC problem in a given period consists of fuel costs of on-line generators, and start-up and shut down costs of units [55].

$$\begin{aligned}\text{Min } F = \sum_{i=1}^{N}\sum_{t=1}^{T} & [F_i(p_{i,t})U_{i,t} \\ & + SU_i\{U_{i,t}(1-U_{i,t-1})\} + SD_i\{U_{i,t}(1-U_{i,t+1})\}]\end{aligned} \tag{1}$$

The fuel cost of each on-line unit is considered as a quadratic function:

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

A simple start-up cost function is used as follows:

$$SU_i = \begin{cases} HSU_i & \text{if } T_{i,off}^t \le T_{i,down} + T_{i,cold} \\ CSU_i & \text{if } T_{i,off}^t > T_{i,down} + T_{i,cold} \end{cases} \tag{3}$$

The objective function of UC problem should be minimized subject to following constrains:

- Power balance equation

In all-time horizons, output power summation of on-line units equals with predicted demand.

$$\sum_{i=1}^{N} p_{i,t} U_{i,t} = PD_t \tag{4}$$

- Power generation limits of units

$$U_{i,t}\, p_{i,\min} \le p_{i,t} \le U_{i,t}\, p_{i,\max} \tag{5}$$

- Reserve constraints

$$\sum_{i=1}^{N} p_{i,\max} U_{i,t} \ge PD_t + R_t \tag{6}$$

- Minimum up and down time of units

$$T_{i,on} \ge T_{i,up} \tag{7}$$

$$T_{i,off} \ge T_{i,down} \tag{8}$$

Minimum up and down time constraints are considered as:

$$U_{i,t} = \begin{cases} 1 & \text{if } T_{i,on} < T_{i,up} \\ 0 & \text{if } T_{i,off} < T_{i,down} \\ 0 \text{ or } 1 & \text{otherwise} \end{cases} \tag{9}$$

- Must-run and must-out units

Some units of system should always be on-line because of system reliability and economic considerations. Also, there are some units which are on-forced outages.

2.2. Proposed method for UC problem solution

Unit Commitment problem consists of "on" and "off" decision for units under different power demand conditions and various constraints, to obtain minimum operational cost. In this paper, the IPPD table method [55] is used to solve UC problem. The following steps indicate the process of UC problem solving by the IPPD table method.

Step 1. The IPPD table is produced. This table specifies the states of committed units for all power demands, without consideration of minimum up and down time constraints. Procedure of the IPPD table formation has been explained at Section 2.2.1.

Step 2. No-load cost of units is considered. If any over-reserve is detected in system, some units are selected for de-commitment.

Step 3. Minimum up and down time constraints are considered and the schedule of final commitment of units has been determined.

Step 4. After obtaining committed units for all power demands, ED sub-problem is solved for on-line units, and the output power of all units is determined. ED problem allocates optimal generation of units based on the incremental fuel cost (λ).

2.3. IPPD and RIPPD tables

The IPPD table is produced by considering output power limits of generators and coefficients of fuel cost functions. The incremental fuel costs are determined by derivative of the fuel cost functions. Fuel cost function of generators is assumed as a quadratic function of output power, according to Eq. (2). So, incremental fuel cost and output power are:

$$\lambda = \frac{dF_i}{dp_i} = b_i + 2c_i p_i \tag{10}$$

$$p_i = (\lambda - b_i)/2c_i \tag{11}$$

To develop the IPPD table following steps are required:

Step 1. Minimum and maximum values of λ for all units in their corresponding $p_{i,\min}$ and $p_{i,\max}$ are determined. Obtained values of λ should be arranged in ascending order and indexed as λ_j ($j = 1,\ldots,2N$).

Step 2. For each λ_j, output power ($p_{i,j}$) of each generator is evaluated. $p_{i,\min}$ and $p_{i,\max}$ are incorporated as:

- If $\lambda_j < \lambda_{i,\min}$ then $p_{j,i} = 0$
- If ($\lambda_j < \lambda_{i,\min}$ & generator is must-run) then $p_{j,i} = p_{i,\min}$
- If $\lambda_j \ge \lambda_{i,\min}$ and $\lambda_j < \lambda_{i,\max}$ then $p_{j,i} = p_{i,\min}$
- If $\lambda_j \ge \lambda_{i,\max}$ then $p_{j,i} = p_{i,\max}$

Step 3. Values of λ, output powers, and sum of output powers (SOP) for each λ, which are arranged in ascending order of λ, form the IPPD table.

In an N-unit system, the IPPD table has $2N$ rows and N+2 columns. First column of the IPPD table is dedicated to λ values, which are arranged in ascending order. Columns 2~N+1 consist of output powers of each unit (i^{th} unit) subject to each λ. Entries of the last column of this table show the sum of unit output powers in each corresponding λ. Assume that the sum of specific power demand and spinning reserve lies between SOP_{j-1} and SOP_j. Then, j-1th and j^{th} rows of the IPPD table are selected. This new table (with $2 \times (N + 2)$ dimensions) is known as Reduced IPPD (RIPPD) table. The RIPPD table consists of information about states of units in selected λ, and transition of committed units from one λ to another one. The IPPD and RIPPD tables for a test system are illustrated in appendix A.

2.4. Commitment of units from the RIPPD table

The "on" and "off" states of units can be determined from the RIPPD table. A new table can be derived, if non-zero entries of the RIPPD, which are corresponding to output powers of generating unit, are replaced by 1. This table is known as Reduced Committed Units (RCU) table [55]. So, the RCU table will have two rows with 0 and 1 entries to show the states of units. The second row of RCU table represents initial state of the committed units.

2.5. Incorporation of no-load cost

The IPPD table is formed based on incremental fuel cost λ, therefore the no-load cost of units isn't considered in its formation. Some of units may have less incremental fuel cost, but huge no-load cost. This matter makes incorporation of no-load cost important for fuel cost reduction.

Medium size generating units may be operated at a lower power than their maximum output power; hence priority list may not exactly describe real fuel cost of these units. In this paper, following approach is used to incorporate no-load cost of generators [55]:

Step 1. Cost per MW at average output power of generating units is calculated.

$$Cost_{index,i} = F_i(P_{i,average}) / P_{i,average} \tag{12}$$

where $P_{i,average} = (P_{i,\min} + P_{i,\max})/2$. This cost index exactly results in the operational cost of the medium size units in less output power than their maximum output power.

Step 2. The units is arranged in ascending order according to their cost indexes to form list of committed units.

Step 3. The last "on" unit in the list of committed units is specified at each time interval. If there is any "off" unit in the left side of the last "on" unit, its state is changed to "on".

2.6. De-commitment of generating units

The committed units may have significant spinning reserve, because of large difference between chosen λ values in the RIPPD table. So, de-commitment of generating units is necessary to reach more economic benefits. If there is extra spinning reserve at "*t*" time interval, the following steps should be done:

Step 1. The committed units after no-load cost consideration are recognized.

Step 2. The last "on" unit in the list of committed units is de-committed, then the spinning reserve is checked. If the spinning reserve constraint after de-commit of the unit is satisfied, that unit remains de-committed.

Step 3. The second step without violating the spinning reserve constraint is repeated.

2.7. Consideration of minimum up and down times of generating units

After obtaining committed units using IPPD, RIPPD, and RCU tables, and no-load cost incorporation, the minimum up and down times constraints should be satisfied.

- If "on" time of a unit is less than its minimum up time, it has to remain "on".
- If "off" time of a unit is less than its minimum down time, it has to remain "off".

Consideration procedure of the minimum up and down times constraints is taken from [19]. This procedure is applied for a 6 unit test system, which have minimum up and down times of 3 hours, in Tables 1 and 2.

Table 1. Incorporation procedure of minimum up time constraint [19].

Time			t-1	t	t+1	
Units states without incorporation of minimum up time	0	1	1	0	0	0
Units states after incorporation of minimum up time	0	1	1	**1**	0	0

Table 2. Incorporation procedure of minimum down time constraint [19].

Time			t-1	t	t+1	
Units states without incorporation of minimum down time	1	1	0	0	1	1
Units states after incorporation of minimum down time	1	1	**1**	**1**	1	1

3. ECONOMIC DISPATCH SUB-PROBLEM

Economic dispatch is scheduling generators to minimize the total operational cost of on-line generators with satisfying all equality and inequality constraints. After identification of the committed units in the UC problem, the ED sub-problem should be solved to reach more economical benefit. In this paper, the analytical "λ-logic" algorithm [59] is used to solve ED sub-problem. The non-iterative nature of "λ-logic" algorithm and its combination with the IPPD table method convert the proposed method to an efficient, simple and suitable approach for solving UC problem, especially in large scale systems.

It should be noted that the "λ-logic" algorithm [59, 60] has a major difference with conventional λ algorithm [5]. In λ algorithm, output power of each unit is calculated for the specified power demand. Then, it is verified that the calculated values satisfy the output power constraints. If output power of any unit is not within its limits, output power of that unit should be set to minimum or maximum. Mostly, it causes to deviate from optimal solution. In this algorithm, it is usually required that the calculation is repeated several times to reach an optimal solution, especially in large scale systems (refer to [5]).

3.1. ED sub-problem formulation

In ED problem, the following objective function is minimized for specified on-line units at each time interval. Suppose that N_t units are active at "t" time interval, which are indexed with j.

$$\min F_{fuel,t} = \sum_{j=1}^{N_t} F_j(p_{j,t}) \tag{13}$$

where the fuel cost function of each on-line unit is considered as a quadratic function as:

$$F_j(p_{j,t}) = a_j + b_j p_{j,t} + c_j p_{j,t}^2 \tag{14}$$

Subject to:

$$\sum_{j=1}^{N_t} p_{j,t} = PD_t \tag{15}$$

$$p_{j,\min} \le p_{j,t} \le p_{j,\max} \tag{16}$$

3.2. Applying "λ-logic" algorithm to ED sub-problem solution

"λ-logic" algorithm has two steps which have to apply for on-line units in each time interval.

Step 1. Pre-prepared power demand data (PPD) is prepared using *"λ-logic"*. This step involves a systematic procedure to obtain a unique PPD for N_t unit system. The PPD acts as an effective factor to reduce computational burden of ED problem.

Step 2. Output power of on-line generators for specified power demand is calculated.

ED condition for economic dispatch of N_t generating units is:

$$\frac{dF_1(p_{1,t})}{dp_{1,t}} = \frac{dF_2(p_{2,t})}{dp_{2,t}} = \cdots = \frac{dF_{N_t}(p_{N_t,t})}{dp_{N_t,t}} = \lambda_t \tag{17}$$

$$\frac{dF_j(p_{j,t})}{dp_{j,t}} = \lambda_{j,t} = b_j + 2c_j p_{j,t} \tag{18}$$

Eq. (18) gives the incremental fuel cost corresponding to $P_{j,t}$ which can be calculated from:

$$p_{j,t} = (\lambda_{j,t} - b_j)/2c_j \tag{19}$$

3.3. Preparation of PPD data for ED sub-problem solution

The following steps are performed to obtain the PPD data.

Step 1. The incremental fuel cost, λ, corresponding to $P_{j,min}$ and $P_{j,max}$ is calculated for each on-line unit. Then, $2N_t$ values are obtained for λ:

$$\lambda_{\min,t} = \left.\frac{dF_j(p_{j,t})}{dp_{j,t}}\right|_{p_{j,t} = p_{j,\min}} \tag{20}$$

$$\lambda_{\max,t} = \left.\frac{dF_j(p_{j,t})}{dp_{j,t}}\right|_{p_{j,t} = p_{j,\max}} \tag{21}$$

Step 2. The obtained λ values are arranged in ascending order.

Step 3. The total power demand at each $\lambda_{J,t}$ is calculated as follow:

- If $\lambda_{J,t} \le \lambda_{j,\min}$ then $p_{j,t} = p_{j,\min}$
- If $\lambda_{J,t} \ge \lambda_{j,\max}$ then $p_{j,t} = p_{j,\max}$
- If $\lambda_{j,\min} \le \lambda_{J,t} \le \lambda_{j,\max}$ then $p_{j,t} = \lambda_{j,t} - b_j/2c_j$

Output power summation of on-line units corresponding to each $\lambda_{J,t}$ forms the PPD data. Then, the PPD table can be tabulated in $2N_t \times 2$ structure. The first column includes $\lambda_{J,t}$ values in ascending order and the second one consists of their corresponding PPD data. The PPD table for a test system is illustrated in appendix B.

3.4. Computation of output power of generating units

The slop in each interval from PPD table is calculated from below equation, and forms m-vector:

$$m_{J,t} = (\lambda_{J+1,t} - \lambda_{J,t})/(PPD_{J+1,t} - PPD_{J,t}) \qquad (22)$$

For any power demand (PD_t), which lies between PPD_J and PPD_{J+1}, the corresponding $\lambda_{PD,t}$ can be obtained [59]:

$$\lambda_{PD,t} = m_{J,t}(PD_t - PPD_{J,t}) + \lambda_{J,t} \qquad (23)$$

Then, the output power of on-line units at "*t*" time interval is calculated as:

- If $\lambda_{PD,t} \le \lambda_{j,\min}$ then $p_{j,t} = p_{j,\min}$
- If $\lambda_{PD,t} \ge \lambda_{j,\max}$ then $p_{j,t} = p_{j,\max}$
- If $\lambda_{j,\min} \le \lambda_{PD,t} \le \lambda_{j,\max}$ then $p_{j,t} = \lambda_{PD,t} - b_j/2c_j$

4. CASE STUDIES AND NUMERICAL RESULTS

The proposed method for UC problem has been simulated in MATLAB software. This method is tested on 10 unit and 40-100 unit systems for UC problem. Flowchart of the proposed method is shown in Fig. 1.

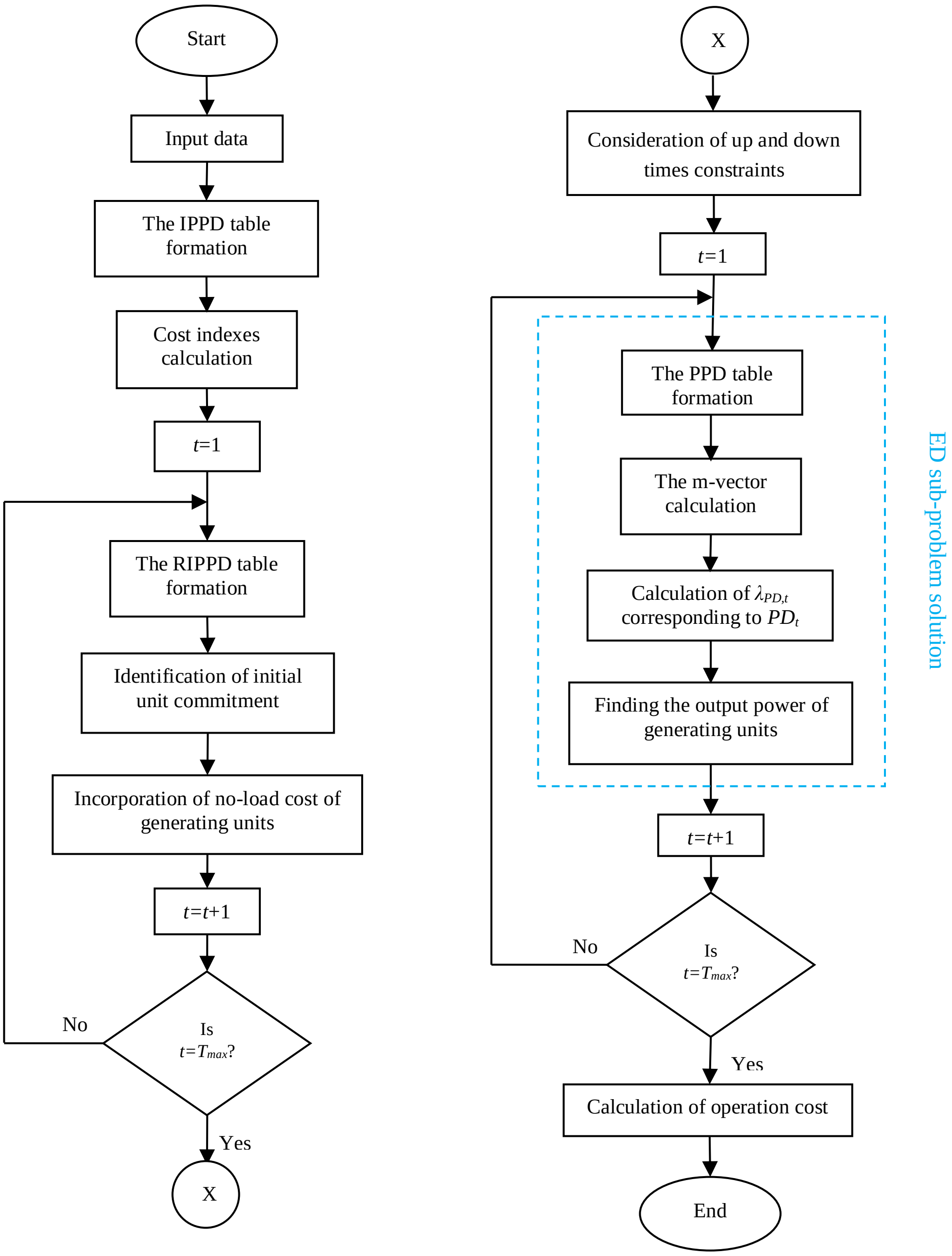

Fig. 1. Flowchart of the proposed method for UC problem

4.1. Test of 10 unit system

In this sub-section, a 10 unit test system is used to indicate the validity and applicability of the proposed method in UC problem. It is supposed that the required reserve is 10% of power demand in each time interval. In this case study, the proposed method is applied to test system with consideration of all constraints: generator limits, minimum up and down times of generating units, and reserve constraint. The resulting schedule of the proposed method for 10 unit test system is represented in Table 3. The output power of each unit for all time intervals from is given in Table 4. Data of 10 unit test system, and power demand for 24 hours can be found in Table 5 [55] and Table 6 [55], recpectively.

Results of 10 unit test system in terms of the total fuel cost and computational time of the proposed method are compared with existing methods such as LR [41], GA [20], EP [26], LRGA [41], and IPPD table and Muller method [55] in Table 7. The results show that the proposed method presents a suitable cost in minimum computational time, compared to other methods.

4.2. Test of 40-100 unit systems

In this case, 40-100 unit systems have been tested. Data for these units come from duplication of 10 unit test system data. Also, power demand of test systems is adjusted according to the system size. The spinning reserve is considered as 10% of power demand. The results of total cost and computational time of the proposed method, in comparison with other methods in literature, are respectively presented in Tables 8 and 9. Because of stochastic nature of some of the methods in

Table 3. Scheduling of the proposed method for 10 unit test system

Hour	Units										Fuel cost ($)	Start-up cost ($)
	1	2	3	4	5	6	7	8	9	10		
1	1	1	0	0	0	0	0	0	0	0	13683	0
2	1	1	0	0	0	0	0	0	0	0	14554	0
3	1	1	0	0	1	0	0	0	0	0	16809	900
4	1	1	0	0	1	0	0	0	0	0	18598	0
5	1	1	0	1	1	0	0	0	0	0	20020	560
6	1	1	1	1	1	0	0	0	0	0	22387	1100
7	1	1	1	1	1	0	0	0	0	0	23262	0
8	1	1	1	1	1	0	0	0	0	0	24150	0
9	1	1	1	1	1	1	1	0	0	0	27251	860
10	1	1	1	1	1	1	1	1	0	0	30058	60
11	1	1	1	1	1	1	1	1	1	0	31916	60
12	1	1	1	1	1	1	1	1	1	1	33890	60
13	1	1	1	1	1	1	1	1	0	0	30058	0
14	1	1	1	1	1	1	1	0	0	0	27251	0
15	1	1	1	1	1	0	0	0	0	0	24150	0
16	1	1	1	1	1	0	0	0	0	0	21514	0
17	1	1	1	1	1	0	0	0	0	0	20642	0
18	1	1	1	1	1	0	0	0	0	0	22387	0
19	1	1	1	1	1	0	0	0	0	0	24150	0
20	1	1	1	1	1	1	1	1	0	0	30058	490
21	1	1	1	1	1	1	1	0	0	0	27251	0
22	1	1	1	1	1	1	1	0	0	0	23593	0
23	1	1	0	0	1	0	0	0	0	0	17685	0
24	1	1	0	0	0	0	0	0	0	0	15427	0
Fuel cost ($)											560744.4662	
Start-up cost ($)											4090.0000	
Total cost ($)											564834.4662	
Computational time											0.1298	

Table 4. Output power of 10 unit test system from ED sub-problem

Hour/Units	1	2	3	4	5	6	7	8	9	10
1	455	245	0	0	0	0	0	0	0	0
2	455	295	0	0	0	0	0	0	0	0
3	455	370	0	0	25	0	0	0	0	0

Table 4. Continued.

4	455	455	0	0	40	0	0	0	0	0
5	455	390	0	130	25	0	0	0	0	0
6	455	360	130	130	25	0	0	0	0	0
7	455	410	130	130	25	0	0	0	0	0
8	455	455	130	130	30	0	0	0	0	0
9	455	455	130	130	85	20	25	0	0	0
10	455	455	130	130	162	33	25	10	0	0
11	455	455	130	130	162	73	25	10	10	0
12	455	455	130	130	162	80	25	43	10	10
13	455	455	130	130	162	33	25	10	0	0
14	455	455	130	130	85	20	25	0	0	0
15	455	455	130	130	30	0	0	0	0	0
16	455	310	130	130	25	0	0	0	0	0
17	455	260	130	130	25	0	0	0	0	0
18	455	360	130	130	25	0	0	0	0	0
19	455	455	130	130	30	0	0	0	0	0
20	455	455	130	130	162	33	25	10	0	0
21	455	455	130	130	85	20	25	0	0	0
22	455	315	130	130	25	20	25	0	0	0
23	455	420	0	0	25	0	0	0	0	0
24	455	345	0	0	0	0	0	0	0	0

Table 5. Data of 10 unit test system [55]

Units	a_i (\$)	b_i (\$/MW)	c_i (\$/MW^2)	$P_{i,\min}$ (MW)	$P_{i,\max}$ (MW)	Cold start cost (\$)	Hot start cost (\$)	Up time (h)	Down time (h)	Cold start hours (h)	Initial status (h)
1	1000	16.19	0.00048	150	455	9000	4500	8	8	5	8
2	970	17.26	0.00031	150	455	10000	5000	8	8	5	8
3	700	16.6	0.00200	20	130	11000	550	5	5	4	-5
4	680	16.5	0.00211	20	130	1120	560	5	5	4	-5
5	450	19.7	0.00398	25	162	1800	900	6	6	4	-6
6	370	22.26	0.00712	20	80	340	170	3	3	2	-3
7	480	27.74	0.00079	25	85	520	260	3	3	2	-3
8	660	25.92	0.00413	10	55	60	30	1	1	0	-1
9	665	27.27	0.00222	10	55	60	30	1	1	0	-1
10	670	27.79	0.00173	10	55	60	30	1	1	0	-1

Table 6. Power demand of 10 unit test system for 24h [55]

Hour (h)	PD (MW)	Hour (h)	PD (MW)	Hour (h)	PD (MW)	Hour (h)	PD (MW)
1	700	7	1150	13	1400	19	1200
2	750	8	1200	14	1300	20	1400
3	850	9	1300	15	1200	21	1300
4	950	10	1400	16	1050	22	1100
5	1000	11	1450	17	1000	23	900
6	1100	12	1500	18	1100	24	800

literature, they need to be run several times. Therefore, the best result of them are selected for comparison in Table 8. For better comparability in Tables 8 and 9, the results which are better than the proposed method are written in italic green, and the best result is written in bold green. It can be seen that:

- For 40 unit test system, the minimum cost is obtained by HDE [61], i.e. 2241564$, and the proposed method has 11th rank with 2244722$.
- For 60 unit test system, the minimum cost is calculated by IQEA [62], i.e. 3362507$, and the proposed method has 3rd rank with 3362694$.
- For 80 unit test system, the minimum cost is obtained by BGWO [25], i.e. 4483381$, and the proposed method has 2nd rank with 4483567$.
- For 100 unit test system, the minimum cost is obtained by the proposed method, i.e. 5601542$.

Table 7. Result comparison of the proposed method with other methods for 10 unit test system

Methods	LR [41]	GA [20]	EP [26]	LRGA [41]	IPPD & Muller [55]	Proposed Method
Total cost ($)	565,825	565825	564,551	564,800	563,977	564,834
Computational time (s)	-	221	100	518	0.516	0.130

Table 8. Comparison of total cost of the proposed method with other methods in literature for 40-100 unit test systems

Methods	Total cost ($)			
	40 units	60 units	80 units	100 units
Lagrangian relaxation (LR) [23]	2250223	-	4496729	5620305
Enhanced adaptive lagrangian relaxation (EALR) [63]	*2244237*	3363491	4485633	5605678
Genetic algorithm (GA) [20]	2251911	3376625	4504933	5627437
Lagrangian relaxation and genetic algorithm (LRGA) [41]	*2242178*	3371079	4501844	5613127
Hybrid continuous relaxation and genetic algorithm (CRGA) [64]	*2243796*	3363338	4485267	5604164
Integer coded genetic algorithm (ICGA) [65]	2254123	3378108	4498943	5630838
Fast genetic algorithm (FGA) [66]	2247336	3367637	4491509	5610855
Intelligent mutation-based genetic algorithm (UCC-GA) [67]	2249715	3375065	4505614	5626514
Ring crossover genetic algorithm (RCGA) [68]	*2242887*	3365337	4486991	5606663
Hybrid genetic algorithm and differential evolution (HGADE) [69]	*2243522*	3362880	4484711	5604787
Evolutionary programming (EP) [26]	2249093	3371611	4498479	5623885
Binary differential evolution (BDE) [70]	2245700	3367066	4489022	5609341
Quantum-inspired evolutionary algorithm (QEA) [62]	2245283	3366272	4487649	5608750
Improved quantum-inspired evolutionary algorithm (IQEA) [62]	*2242982*	**3362507**	4484088	5603355
Hybrid differential evolution (HDE) [61]	**2241564**	-	-	-
Seeded memetic (SM) [23]	2249589	-	4494214	5616314
Local search method (LCM) [71]	2245930	3369586	4486644	5607840
Absolute stochastic simulated annealing (ASSA) [39]	*2244182*	3366184	4487939	5608862
IPPD & Muller [55]	2247162	3366874	4490208	5609782
Enhanced simulated annealing (ESA) [23]	2250063	-	4498076	5617876
Particle swarm optimization (PSO) [29]	2250012	3374174	4501538	5625376
Improved particle swarm optimization (IPSO) [29]	2248163	3370979	4495032	5619284
Binary particle swarm optimization (BPSO) [72]	*2243210*	-	4487388	5608172
Improved binary particle swarm optimization (IBPSO) [40]	2248581	3367865	4491083	5610293
Mutation-based particle swarm optimization (MPSO) [73]	2323435	3451762	4691481	5864719
Local convergence averse binary PSO (LCA-PSO) [73]	2277396	3420438	4554346	5706201
Binary grey wolf optimizer (BGWO) [25]	*2244701*	*3362515*	**4483381**	5604146
Binary Coded Modified Moth Flame Optimization Algorithm (BMMFOA) [35]	2245806	3365139	4488327	5608202
Proposed Method	2244722	3362694	4483567	**5601542**

- For all 40-100 unit test systems, the proposed method has the minimum computational time (less than 0.3s).

For heuristic methods, it is required to remind that the best result of multiple runs are reported in Table 8. For example, in 80 unit test system the average result for BGWO [25] is 4486675$, and in 60 unit test system the average result for IQEA [62] and BGWO [25] are respectively 3363458$ and 3366488$, which all are more than by the proposed method.

Table 9. Comparison of computational time of the proposed method with other methods in literature for 40-100 unit test systems

Methods	Computational time (s)			
	40 units	60 units	80 units	100 units
Lagrangian relaxation (LR) [23]	-	-	-	-
Enhanced adaptive lagrangian relaxation (EALR) [63]	52	113	209	345
Genetic algorithm (GA) [20]	2697	5840	10036	15733
Lagrangian relaxation and genetic algorithm (LRGA) [41]	2165	2414	3383	4045
Hybrid continuous relaxation and genetic algorithm (CRGA) [64]	265	541	937	1575
Integer coded genetic algorithm (ICGA) [65]	58.3	117.3	176	242.5
Fast genetic algorithm (FGA) [66]	29	42	60	75
Intelligent mutation-based genetic algorithm (UCC-GA) [67]	614	1085	1975	3547
Ring crossover genetic algorithm (RCGA) [68]	-	-	-	-
Hybrid genetic algorithm and differential evolution (HGADE) [69]	123	277	343	397
Evolutionary programming (EP) [26]	1176	2267	3584	6120
Binary differential evolution (BDE) [70]	-	-	-	-
Quantum-inspired evolutionary algorithm (QEA) [62]	93	120	151	182
Improved quantum-inspired evolutionary algorithm (IQEA) [62]	146	191	235	293
Hybrid differential evolution (HDE) [61]	2394	-	-	-
Seeded memetic (SM) [23]	-	-	-	-
Local search method (LCM) [71]	1.2	1.8	2.8	4
Absolute stochastic simulated annealing (ASSA) [39]	228.52	561.48	1095.38	1843.19
IPPD & Muller [55]	6.494	17.387	31.225	46.549
Enhanced simulated annealing (ESA) [23]	88.28	-	405.1	696.43
Particle swarm optimization (PSO) [29]	-	-	-	-
Improved particle swarm optimization (IPSO) [29]	-	-	-	-
Binary particle swarm optimization (BPSO) [72]	-	-	-	-
Improved binary particle swarm optimization (IBPSO) [40]	260	327	542	872
Mutation-based particle swarm optimization (MPSO) [73]	317.29	673.46	673.46	2122.44
Local convergence averse binary PSO (LCA-PSO) [73]	274.67	572.3	1068.58	1734.67
Binary grey wolf optimizer (BGWO) [25]	153.5	268.2	469.6	822.23
Binary Coded Modified Moth Flame Optimization Algorithm (BMMFOA) [35]	118.25	274.45	398.98	723.567
Proposed Method	**0.1643**	**0.2062**	**0.2366**	**0.2875**

5. CONCLUSIONS

In this paper, a new analytical and non-iterative method using IPPD table and *“λ-logic”* algorithm has been proposed for UC problem, with consideration of different constraints. The IPPD table has been used to solve UC problem, and ED sub-problem has been solved by *“λ-logic”* algorithm. Computational time of the proposed method is considerably less than other methods in literature. Results indicate the validity and applicability of the proposed method to solve UC problem, especially in large scale systems. As a future work, transmission limits can also be considerd in constraints of UC problem.

Appendix A.

The IPPD and RIPPD tables of 10 unit test system are shown in Tables A.1 and A.2, respectively. The RIPPD table is formed for time interval t=10, which is corresponding to PD_t=1400MW and R_t=140MW.

Appendix B.

The PPD table, which is used in solving of ED sub-problem, is shown in Table B.1 for t=9. It should be noted that in this time interval, 7 units are “on” according to final state of committed units. So, the PPD table for this time interval has a 14×2 structure.

Table A.1. IPPD table for 10-unit test system

Lambda ($/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)
16.334	150	0	0	0	0	0	0	0	0	0	150
16.584	150	0	0	20	0	0	0	0	0	0	170
16.627	455	0	0	20	0	0	0	0	0	0	475
16.68	455	0	20	20	0	0	0	0	0	0	495
17.049	455	0	20	130	0	0	0	0	0	0	605
17.12	455	0	130	130	0	0	0	0	0	0	715
17.353	455	150	130	130	0	0	0	0	0	0	865
17.542	455	455	130	130	0	0	0	0	0	0	1170
19.899	455	455	130	130	25	0	0	0	0	0	1195
20.99	455	455	130	130	162	0	0	0	0	0	1332
22.545	455	455	130	130	162	20	0	0	0	0	1352
23.399	455	455	130	130	162	80	0	0	0	0	1412
26.003	455	455	130	130	162	80	0	10	0	0	1422
26.374	455	455	130	130	162	80	0	55	0	0	1467
27.314	455	455	130	130	162	80	0	55	10	0	1477
27.514	455	455	130	130	162	80	0	55	55	0	1522
27.779	455	455	130	130	162	80	25	55	55	0	1547
27.825	455	455	130	130	162	80	25	55	55	10	1557
27.874	455	455	130	130	162	80	85	55	55	10	1617
27.980	455	455	130	130	162	80	85	55	55	55	1662

Table A.2. RPPD table for 10 unit test system at time interval 10

Lambda ($/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)
27.514	455	455	130	130	162	80	0	55	55	0	1522
27.779	455	455	130	130	162	80	25	55	55	0	1547

Table B.1. PPD table for 10-unit test system at time interval 9

Lambda ($/MW)	PPD (MW)
16.334	410
16.584	670.83
16.627	725.05
16.68	737.65
17.049	917.15
17.12	935
17.353	935
17.542	1240
19.899	1240
20.99	1377
22.545	1377
23.399	1437
27.779	1437
27.874	1497

REFERENCES

[1] R. Kerr, J. Scheidt, A. Fontanna and J. Wiley, "Unit commitment," *IEEE Trans. Power App. Syst.*, no. 5, pp. 417-21, 1966.

[2] A. Hatefi and R. Kazemzadeh, "Intelligent tuned harmony search for solving economic dispatch problem with valve-point effects and prohibited operating zones," *J. Oper. Autom. Power Eng.*, vol. 1, no. 2, 2013.

[3] R. Sedaghati, F. Namdari, "An intelligent approach based on meta-heuristic algorithm for non-convex economic dispatch," *J. Oper. Autom. Power Eng.*, vol. 3, no. 1, pp. 47-55, 2015.

[4] E. Dehnavi, H. Abdi and F. Mohammadi, "Optimal emergency demand response program integrated with multi-objective dynamic economic emission dispatch problem," *J. Oper. Autom. Power Eng.*, vol. 4, no. 1, pp. 29-41, 2016.

[5] A. J. Wood and B. F. Wollenberg. Power generation, operation, and control, Wiley, 1996.

[6] R. Quan, J. Jian and L. Yang, "An improved priority list and neighborhood search method for unit commitment," *Int. J. Electr. Power Energy Syst.*, vol. 67, pp. 278-85, 2015.

[7] W. L. Snyder, H. D. Powell and J. C. Rayburn, "Dynamic programming approach to unit commitment," *IEEE Trans. Power Syst.*, vol. 2, no. 2, pp. 339-48, 1987.

[8] A. I. Cohen and M. Yoshimura, "A branch-and-bound algorithm for unit commitment," *IEEE Trans. Power App. Syst.*, no. 2, pp. 444-51, 1983.

[9] T. S. Dillon, K. W. Edwin, H. D. Kochs and R. Taud, "Integer programming approach to the problem of

optimal unit commitment with probabilistic reserve determination," *IEEE Trans. Power App. Syst.*, no. 6, pp. 2154-66, 1978.

[10] M. Carrión and J. M. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1371-8, 2006.

[11] L. Yang, J. Jian, Y. Wang and Z. Dong, "Projected mixed integer programming formulations for unit commitment problem," *Int. J. Electr. Power Energy Syst.*, vol. 68, pp. 195-202, 2015.

[12] A. Viana and J. P. Pedroso, "A new MILP-based approach for unit commitment in power production planning," *Int. J. Electr. Power Energy Syst.*, vol. 44, no. 1, pp. 997-1005, 2013.

[13] S. Virmani, E. C. Adrian, K. Imhof and S. Mukherjee, "Implementation of a Lagrangian relaxation based unit commitment problem," *IEEE Trans. Power Syst.*, vol. 4, no. 4, pp. 1373-80, 1989.

[14] X. Feng and Y. Liao, "A new Lagrangian multiplier update approach for Lagrangian relaxation based unit commitment," *Electr. Power Compon. Syst.*, vol. 34, no. 8, pp. 857-66, 2006.

[15] X. Sun, P. Luh, M. Bragin, Y. Chen, J. Wan and F. Wang, "A novel decomposition and coordination approach for large day-ahead unit commitment with combined cycle units," *IEEE Trans. Power Syst.*, 2018.

[16] V. S. Pappala and I. Erlich, "A new approach for solving the unit commitment problem by adaptive particle swarm optimization," Proc. of *IEEE PES Gen. Meeting*, Pittsburgh, 2008, pp. 1-6.

[17] G. V. S. Reddy and V. Ganesh, C. S. Rao, "Implementation of clustering based unit commitment employing imperialistic competition algorithm," *Int. J. Electr. Power Energy Syst.*, vol. 82, pp. 621-8, 2016.

[18] H. Sasaki, M. Watanabe, J. Kubokawa, N. Yorino and R. Yokoyama, "A solution method of unit commitment by artificial neural networks," *IEEE Trans. Power Syst.*, vol. 7, no. 3, pp. 974-81, 1992.

[19] V. N. Dieu and W. Ongsakul, "Ramp rate constrained unit commitment by improved priority list and augmented Lagrange Hopfield network," *Electr. Power Syst. Res.*, vol. 78, no. 3, pp. 291-301, 2008.

[20] S. A. Kazarlis, A. Bakirtzis and V. Petridis, "A genetic algorithm solution to the unit commitment problem," *IEEE Trans. Power Syst.*, vol. 11, no. 1, pp. 83-92, 1996.

[21] J. M. Arroyo and A. J. Conejo, "A parallel repair genetic algorithm to solve the unit commitment problem," *IEEE Trans. Power Syst.*, vol. 17, no. 4, pp. 1216-24, 2002.

[22] D. Simopoulos and G. Contaxis, "Unit commitment with ramp rate constraints using the simulated annealing algorithm," Proc. IEE *Meditraneh Electrotech. Conf.*, 2004, pp. 845-9.

[23] D. N. Simopoulos, S. D. Kavatza and C. D. Vournas, "Unit commitment by an enhanced simulated annealing algorithm," *IEEE Trans. Power Syst.*, vol. 21, no. 1, pp. 68-76, 2006.

[24] K. Srikanth, L. K. Panwar, B. Panigrahi, E. Herrera-Viedma, A. K. Sangaiah and G.-G. Wang, "Meta-heuristic framework: quantum inspired binary grey wolf optimizer for unit commitment problem," *Comput. Electr. Eng.*, 2017.

[25] L. K. Panwar, S. Reddy K, A. Verma, B. K. Panigrahi and R. Kumar, "Binary Grey wolf optimizer for large scale unit commitment problem," *Swarm Evol. Comput.*, vol. 38, pp. 251-66, 2018.

[26] K. Juste, H. Kita, E. Tanaka and J. Hasegawa, "An evolutionary programming solution to the unit commitment problem," *IEEE Trans. Power Syst.*, vol. 14, no. 4, pp. 1452-9, 1999.

[27] Y. W. Jeong, J. B. Park, J. R. Shin and K. Y. Lee, "A thermal unit commitment approach using an improved quantum evolutionary algorithm," *Electr. Power Compon. Syst.*, vol. 37, no. 7, pp. 770-86, 2009.

[28] A. Trivedi, D. Srinivasan, K. Pal, C. Saha and T. Reindl, "Enhanced multiobjective evolutionary algorithm based on decomposition for solving the unit commitment problem," *IEEE Trans. Ind. Inf.*, vol. 11, no. 6, pp. 1346-57, 2015.

[29] B. Zhao, C. Guo, B. Bai and Y. Cao, "An improved particle swarm optimization algorithm for unit commitment," *Int. J. Electr. Power Energy Syst.*, vol. 28, no. 7, pp. 482-90, 2006.

[30] T. Ting, M. Rao and C. Loo, "A novel approach for unit commitment problem via an effective hybrid particle swarm optimization," *IEEE Trans. Power Syst.*, vol. 21, no. 1, pp. 411-8, 2006.

[31] G. Xiong, X. Liu, D. Chen, J. Zhang and T. Hashiyama, "PSO algorithm-based scenario reduction method for stochastic unit commitment problem," *IEEJ Trans. Electr. Electron. Eng.*, vol. 12, no. 2, pp. 206-13, 2017.

[32] S. P. Simon, N. P. Padhy and R. Anand, "An ant colony system approach for unit commitment problem," *Int. J. Electr. Power Energy Syst.*, vol. 28, no. 5, pp. 315-23, 2006.

[33] C. C. A. Rajan and M. Mohan, "An evolutionary programming-based tabu search method for solving the unit commitment problem," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 577-85, 2004.

[34] F. Barani, M. Mirhosseini, H. Nezamabadi-pour and M. M. Farsangi, "Unit commitment by an improved binary quantum GSA," *Appl. Soft Comput.*, vol. 60, pp. 180-9, 2017.

[35] S. Reddy, L. K. Panwar, B. Panigrahi and R. Kumar, "Solution to unit commitment in power system operation planning using binary coded modified moth flame optimization algorithm (BMMFOA): A flame selection based computational technique," *J. Comput. Sci.*, 2017.

[36] M. Xie, Y. Zhu, S. Ke, Y. Du and M. Liu, "Ordinal optimization theory to solve large-scale power system unit commitment," *IEEJ Trans. Electr. Electron. Eng.*, 2018.

[37] S. Reddy K, L. Panwar, B. Panigrahi and R. Kumar, "Binary whale optimization algorithm: a new metaheuristic approach for profit-based unit commitment problems in competitive electricity markets," *Eng. Optim.*, pp. 1-21, 2018.

[38] L. Yang, C. Zhang, J. Jian, K. Meng, Y. Xu and Z. Dong, "A novel projected two-binary-variable formulation for unit commitment in power systems," *Appl. Energy*, vol. 187, pp. 732-45, 2017.

[39] A. Y. Saber, T. Senjyu, T. Miyagi, N. Urasaki and T. Funabashi, "Absolute stochastic simulated annealing approach to unit commitment problem," Proc. *13th Int. Conf. Intell. Syst. Appl. Power Syst.*, Arlington, 2005.

[40] X. Yuan, H. Nie, A. Su, L. Wang and Y. Yuan, "An improved binary particle swarm optimization for unit commitment problem," *Expert Syst. Appl.*, vol. 36, no. 4, pp. 8049-55, 2009.

[41] C. P. Cheng, C. W. Liu, C. C. Liu, "Unit commitment by Lagrangian relaxation and genetic algorithms," *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 707-14, 2000.

[42] P. Sriyanyong and Y. Song, “Unit commitment using particle swarm optimization combined with Lagrange relaxation,” Proc. *IEEE PES Gen. Meeting,*, 2005, pp. 2752-9.

[43] F. Rouhi and R. Effatnejad, “Unit commitment in power system by combination of dynamic programming, genetic algorithm and particle swarm optimization (PSO),” *Indian J. Sci. Technol.,* vol. 8, no. 2, p. 134, 2015.

[44] S. Halilcevic and I. Softic, “Degree of optimality as a measure of distance of power system operation from optimal operation,” *J. Oper. Autom. Power Eng.,* vol. 6, no. 1, pp. 69-79, 2018.

[45] T. Victoire and A. Jeyakumar, “Unit commitment by a tabu-search-based hybrid-optimisation technique,” *IET Gener. Transm. Distrib.*, pp. 563-74, 2005.

[46] P. Attaviriyanupap, H. Kita, E. Tanaka and J. Hasegawa, “A hybrid LR-EP for solving new profit-based UC problem under competitive environment,” *IEEE Trans. Power Syst.,* vol. 18, no. 1, pp. 229-37, 2003.

[47] T. Logenthiran and W. L. Woo, “Lagrangian relaxation hybrid with evolutionary algorithm for short-term generation scheduling,” *Int. J. Electr. Power Energy Syst.,* vol. 64, pp. 356-64, 2015.

[48] C. S. Sundaram, M. Sudhakaran and P. A. D. V. Raj, “Tabu search-enhanced artificial bee colony algorithm to solve profit-based unit commitment problem with emission limitations in deregulated electricity market,” *Int. J. Metaheuristics,* vol. 6, no. 1-2, pp. 107-32, 2017.

[49] V. K. Kamboj, “A novel hybrid PSO–GWO approach for unit commitment problem,” *Neural Comput. Appl.,* vol. 27, no. 6, pp. 1643-55, 2016.

[50] Z. Yang, K. Li, Q. Niu and Y. Xue, “A novel parallel-series hybrid meta-heuristic method for solving a hybrid unit commitment problem,” *Knowledge Based Syst.,* vol. 134, pp. 13-30, 2017.

[51] M. Nemati, M. Braun and S. Tenbohlen, “Optimization of unit commitment and economic dispatch in microgrids based on genetic algorithm and mixed integer linear programming,” *Appl. Energy,* vol. 210, pp. 944-63, 2018.

[52] H. Anand, N. Narang and J. Dhillon, “Profit based unit commitment using hybrid optimization technique,” *Energy,* vol. 148, pp. 701-15, 2018.

[53] S. Prabakaran and S. Tamilselvi, P. A. D. V. Raj, M. Sudhakaran, S. Rajasekar, "Solution for multi-area unit commitment problem using PSO-based modified firefly algorithm", *Adv. Syst. Control Autom.*, Springer; 2018. pp. 625-36.

[54] S. Hemamalini and S. P. Simon, “Dynamic economic dispatch using maclaurin series based lagrangian method,” *Energy Convers. Manage.,* vol. 51, no. 11, pp. 2212-9, 2010.

[55] K. Chandram and N. Subrahmanyam, M. Sydulu, “Unit commitment by improved pre-prepared power demand table and muller method,” *Int. J. Electr. Power Energy Syst.,* vol. 33, no. 1, pp. 106-14, 2011.

[56] Q. P. Zheng, J. Wang and A. L. Liu, “Stochastic optimization for unit commitment-A review,” *IEEE Trans. Power Syst.,* vol. 30, no. 4, pp. 1913-24, 2015.

[57] B. Saravanan, S. Das, S. Sikri and D. Kothari, “A solution to the unit commitment problem—a review,” *Front. Energy,* vol. 7, no. 2, pp. 223-36, 2013.

[58] I. Abdou and M. Tkiouat, “Unit commitment problem in electrical power system: a literature review,” *Int. J. Electr. Comput. Eng.,* vol. 8, no. 3, 2018.

[59] A. Theerthamalai and S. Maheswarapu, “An effective non-iterative “ λ-logic based” algorithm for economic dispatch of generators with cubic fuel cost function,” *Int. J. Electr. Power Energy Syst.,* vol. 32, no. 5, pp. 539-42, 2010.

[60] S. Sajjadi and R. Kazemzadeh, “A new analytical maclaurin series based λ-logic algorithm to solve the non-convex economic dispatch problem considering valve-point effect,” *Iran. J. Electr. Comput. Eng.,* vol. 12, no. 1-2, pp. 63-9, 2013.

[61] V. K. Kamboj, S. Bath and J. Dhillon, “A novel hybrid DE–random search approach for unit commitment problem,” *Neural Comput. .Appl.,* vol. 28, no. 7, pp. 1559-81, 2017.

[62] C. Chung, H. Yu and K. P. Wong, “An advanced quantum-inspired evolutionary algorithm for unit commitment,” *IEEE Trans. Power Syst.,* vol. 26, no. 2, pp. 847-54, 2011.

[63] W. Ongsakul and N. Petcharaks, “Unit commitment by enhanced adaptive Lagrangian relaxation,” *IEEE Trans. Power Syst.,* vol. 19, no. 1, pp. 620-8, 2004.

[64] K.-i. Tokoro, Y. Masuda and H. Nishino, “Soving unit commitment problem by combining of continuous relaxation method and genetic algorithm,” Proc. *SICE Annual Conf.,* 2008, pp. 3474-8.

[65] I. G. Damousis, A. G. Bakirtzis and P. S. Dokopoulos, “A solution to the unit-commitment problem using integer-coded genetic algorithm,” *IEEE Trans. Power Syst.,* vol. 19, no. 2, pp. 1165-72, 2004.

[66] T. Senjyu, H. Yamashiro, K. Shimabukuro, K. Uezato and T. Funabashi, “Fast solution technique for large-scale unit commitment problem using genetic algorithm,” *IET Gener. Transm. Distrib.,* vol. 150, no. 6, pp. 753-60, 2003.

[67] T. Senjyu, H. Yamashiro, K. Uezato and T. Funabashi, “A unit commitment problem by using genetic algorithm based on unit characteristic classification,” Proc. *IEEE PES Winter Meeting*, 2002, pp. 58-63.

[68] S. B. A. Bukhari, A. Ahmad, S. A. Raza and M. N. Siddique, “A ring crossover genetic algorithm for the unit commitment problem,” *Turk. J. Electr. Eng. Comput. Sci.,* vol. 24, no. 5, pp. 3862-76, 2016.

[69] A. Trivedi, D. Srinivasan, S. Biswas and T. Reindl, “A genetic algorithm–differential evolution based hybrid framework: case study on unit commitment scheduling problem,” *Inf. Sci.,* vol. 354, pp. 275-300, 2016.

[70] Y. W. Jeong and W. N. Lee, H. H. Kim, J. B. Park, J. R. Shin, “Thermal unit commitment using binary differential evolution,” *J. Electr. Eng. Technol.,* vol. 4, no. 3, pp. 323-9, 2009.

[71] L. Fei and L. Jinghua, “A solution to the unit commitment problem based on local search method,” Proc. *Int. conf. ICEET,* 2009, pp. 51-6.

[72] Y. W. Jeong, J. B. Park, S. H. Jang and K. Y. Lee, “A new quantum-inspired binary PSO for thermal unit commitment problems,” Proc. *Int. conf. ISAP,* 2009, pp. 1-6.

[73] B. Wang, Y. Li and J. Watada, “Re-scheduling the unit commitment problem in fuzzy environment,” Proc. *IEEE Int. conf. Fuzz. Syst.*, 2011, pp. 1090-5.