Optimizing Thermal Generation Scheduling Using Truncated Dynamic Programming Techniques

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Abstract- In this paper, we examine the optimal solution to the thermal generation scheduling problem using three versions of Dynamic Programming (DP), Conventional DP (CDP), Sequential Combination DP (SC-DP), and Truncated Combination DP (TC-DP) to solve the Unit Commitment (UC) problem. The Unit Commitment (UC), one of the essential problems in power system applications, consists of producing a minimum cost output schedule for a setting horizon while satisfying the units constraints on the system generation as a whole. The lambda-iteration technique is applied to solve the embedded economic dispatch sub-problem. The presented techniques are implemented for 5-unit and 10-unit thermal systems for 24-hour. In comparative simulation results, it is shown that the CDP can find accurate solutions for smaller systems, but it is computationally expensive for large systems. In order to strike a better trade-off between solution quality and computational efficiency, TC-DP inevitably prunes non-promising decision paths, making it more efficient than classical DP by reducing the state-space explosion. The Results indicate that TC-DP is an efficient and scalable optimization framework for modern complex power systems.

Keywords– Unit Commitment, Dynamic Programming, Economic Dispatch, Thermal Generation, Optimization.

1. INTRODUCTION

The need for electrical energy exhibits a distinct cyclical pattern influenced by human activities; nevertheless, satisfying this demand at the minimum cost while ensuring system security poses a significant challenge for utilities and power system operators. The goal of this short-term optimization challenge is to plan the generator start-ups, shutdowns, and identify their production levels to satisfy the forecasted demand for the short term. The goal of this short-term optimization is to reduce the costs associated with production and the start-up/shut-down of all generating units within a timeframe of 24 hours or, at most, 168 hours, while adhering to all operational constraints [1].

The UC issue needs to identify the ON/OFF condition of the generation units for every hour of the planning timeframe and effectively allocate the load across the active units. The most important optimisation for power system operations is UC. The UC problem for large power systems must therefore be computationally efficient. UC problems become exponentially complex with the increase in the number of producing units [2]. Thermal power generation fulfils most of the power demands for most of linked power systems. There are many operating strategies that could be employed to meet the hourly varying power consumption required during the day. Choose an optimum or sub-optimal operating plan based on the economics. Additionally, in this situation, thermal unit commitment (UC) represents one of the most sophisticated methods for delivering dependable and cost-effective electricity to consumers [3,4].

The paper is structured in the following way: Section 2 addresses the UC formulation. Section 3 illustrates how to solve UC using DP. Section 4 applies this technique to a sample generation system consisting of 5 units over a 24-hour load period and 10 units over a 24-hour load period, comparing the simulation results, and Section 5 ends the article.

2. PROBLEM DEFINITION AND CONSTRAINTS

Over a 24-h study horizon, UC aims to optimize the hourly commitment of the set of available generating units. It costs money to start up producing units and leaving them un-deployed as well [5,6]. The total cost throughout the lifetime of the study should be as low as possible. Mathematically, the function to be minimised as:

$$C(P_{gk}^{t}, U_{k,t}) = \sum_{t=1}^{T}\sum_{k=1}^{M}[C_k(P_{gk}^{t}) + ST_{k,t}(1 - U_{k,t-1})]\, U_{k,t} \quad (1)$$

subject to the below constraints

(a) constraint for power balance

$$P_{load}^{t} - \sum_{k=1}^{M} P_{gk}^{t} U_{k,t} = 0 \quad (2)$$

(b) spinning reserve constraint

$$P_{load}^{t} + R^{t} - \sum_{k=1}^{M} P_{gk,max} U_{k,t} \leq 0 \quad (3)$$

(c) generation limit constraints

$$P_{gk,min} U_{k,t} \leq P_{gk}^{t} \leq P_{gk,max} U_{k,t}; k = 1,2, \ldots .. N \quad (4)$$

(d) start-up cost

$$ST_{k,t} = \begin{cases} HST_k; if T_{k,down} \leq T_{k,off} \leq T_{k,cold} + T_{k,down} \\ CST_k; if T_{k,off} > T_{k,cold} + T_{k,down} \end{cases} \quad (5)$$

(e) Constraints for minimum up time and down time

$$U_{k,t} = \begin{cases} 1; if T_{k,on} < T_{k,up} \\ 0; if T_{k,off} < T_{k,down} \end{cases} \quad (6)$$

where

$C_k(P_{gk}^t)$ – The function of fuel cost for the k^{th} unit, having a generation output P_{gk}^t during t^{th} hour. Typically, it is a quadratic polynomial featuring coefficients a_k, b_k and c_k structured as follows:

$$C_k(P_{gk}^t) = a_k + b_k P_{gk}^t + c_k (P_{gk}^t)^2$$

M – Quantity of Units

T – Total hours

P_{gk}^t – Output generation of the k^{th} unit during t^{th} hour in MW

$ST_{k,t}$ - The k^{th} unit's start-up cost in \$ during t^{th} hour

$U_{k,t}$- indicates the on/off conditions of the k^{th} unit during t^{th} hour, where 1 means on and 0 means off

P_{load}^t- Demanded load during t^{th} hour in MW

R^t- The spinning reserve of the system during t^{th} hour (MW)

$P_{k,max}$- Maximum generation power limit of k^{th} unit (MW)

$P_{k,min}$- Minimum generation limit of k^{th} unit (MW)

HST_k- Cost of hot start-up for k^{th} unit (\$)

CST_k- Cost of cold start-up for k^{th} unit (\$)

$T_{k,down}$ - The k^{th} unit's minimum down time expressed in hours

$T_{k,up}$ - The k^{th} unit's minimum down time in hour

$T_{k,off}$ – The total hours that the k^{th} unit remains continuously off

$T_{k,on}$ - Consistently at the time of the k^{th} unit in hour

$T_{k,cold}$ - Hours of cold startup for the k^{th} unit expressed in hours

3. DYNAMIC PROGRAMMING

Optimization-based methods such as dynamic programming is among the first terms introduced and it was originally coined by Richard Bellman for 1940 to address problems that required a sequence of optimal decisions. He had sharpened this to its modern meaning by 1953. This domain was established as a subsystem analysis & engineering domain as labelled by IEEE. The Bellman equation is a key dynamic programming result which reformulates an optimal control problem in a recursive form, named after Bellman. Bellman equations (also known as dynamic programming equations) are, the discovered by Richard Bellman, a key condition for optimality, in dynamic programming. It has been used since the 1960s to address the UC problem and is still widely used today around the world [7].

The term "dynamic programming" does not relate to computer programming; rather, it stems from mathematical programming, which is synonymous with optimization. Accordingly, the "program" represents the optimal action plan that is produced. As an example, a program at an exhibition can sometimes mean a detailed layout of events [8].

The DP method utilises a systematic multistage searching algorithm that seeks to find the best solution possible without the need to access all the combinations available. In the earlier attempts, the commitment of generation units was performed individually for each instance. In terms of time, each stage is allocated with the output levels of a generating unit, the overall number of phases corresponds to the number of units in the system. If we assume that the startup cost was identical for every unit, then the cost at each output level was the total of the production expenses and the startup costs. This posed a major constraint, as it failed to account for the interaction of adjacent time intervals, and therefore, could not accurately represent the time-sensitive start-up expense. Additionally, it was unable to adequately manage the minimum up and down time limitations unless certain heuristic methods were incorporated [9].

3.1 UC Solution using DP

Dynamic Programming (DP) is a major optimising method, which is used in many applications. It breaks down two, solves them one by one, and eventually yields an optimal solution to the higher-level question. Its wrinkles are recursively applied from subproblems to provide the best solution. In its simplest version, the dynamic programming technique for the unit commitment issue examines every potential state that might arise in each time period. Next, we can immediately discard some of these states because they are determined to be infeasible. Nonetheless, for anything resembling an average sized utility, there will be a huge number of feasible states and the time to solve to any measure will be far beyond the capabilities of the fastest computers. This is one of the reasons many of the proposed solutions are not complete simplifications from the dynamic programming process. Under the current CDP method, the result is indeed valid and best over the limited area but needs a considerable memory space and is time-consuming to gain a domestic optimum solution [10,11]. Consider 24 hr load is supplied by four units. Therefore, the overall maximum route to meet the 24-hour load profile is established as follows:

$$TotalPaths = (2^4 - 1)^{24}$$

In order to overcome this drawback, the sequential combination DP and the truncation combination DP are used to solve UC problem. These two strategies have one main economic benefit, they reduce the dimensionality of the problem. Other advantages are its adaptivity and flexibility, which can easily be adapted to replicate the properties of some utilities. In addition, estimate of manufacturing costs also was near the optimal solution [12].

Both SC-DP and TC-DP impose a strict ordering of units. In TC-DP, the number of units is selected with tight priority sequence such that the committed units for each hour during the load period meet the load demand with the maximum level proposed by the optimizer. The probable states for each hour are determined on the basis of the units that were committed. A feasible state where the committed units may provide the necessary load and fulfil the capacity required during each period [7].

3.2 Forward DP Approach

Utilize forward dynamic programming comprising a forward recursion phase to identify optimal paths to all reachable states at each stage, followed by a backward recursion phase to extract the best solution starting from the feasible final state with the minimum cumulative cost. [8]. A DP algorithm could be created to operate in reverse chronological order, beginning at the final hour and proceeding back to the first. The algorithm might just be progressing through time, moving from the first hour to the last hour. For problems like the generator UC problem, the forward technique provides some benefits. For example, when unit's start-up expense depends on the duration it has remained off-line, a forward dynamic programming method is more appropriate, as the unit's past history can be approximated at each optimization stage. For other pragmatic considerations for why we should proceed with DP. They require easy initial conditions to be set, and the computations can be made for as much long as needed [10]. Flowchart for a forward DP method is depicted in Figure 1.

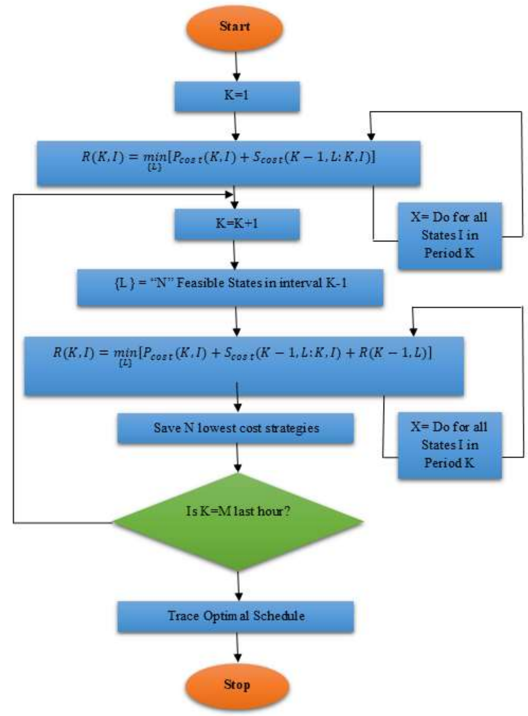

Figure 1: Truncated Dynamic Programming flow for thermal generation scheduling

The recursive method to calculate the lowest cost during i^{th} hour with i^{th} combination is

$$R(K,I) = \min_{\{L\}} \begin{bmatrix} P_{cos\,t}(K,I) + S_{cos\,t}(K-1,L:K,I) \\ +R(K-1,L) \end{bmatrix} \quad (7)$$

where

$R(K,I)$ – Denotes return function (Lowest total cost to reach at state (K,I)

$P_{cos\,t}(K,I)$ – Cost of production for state (K,I)

$S_{cos\,t}(K-1,L:K,I)$ -Transition cost from state $(K-1,L)$ to state (K,I)

State(K,I) - I^{th} combination in k^{th} hour

4. SIMULATION BASED ASSESSMENT

The prior sections offer a detailed understanding of the UC issue and how it can be formulated via DP. Various DP techniques which are described in Section III have been used to tackle the thermal UC issue. The performance is investigated for the 5 generator and 10 generator test data. Explaining what the results are for each system:

4.1 Test System 1

Five units will be allocated to meet a 24-hour load profile. The data for input and load is obtained from [13].

4.1.1 Performance Evaluation of Conventional DP (CDP)

In this case, as we saw before, we fully enumerated all the units. UC timetable for 5 units over a 24-hr period is shown in Table 1. P_{cost} represents the cost of production by generators that are on-line every hour based on the schedule presented in Table 2.

Table 1: UC Schedule for CDP

	Units				
hour	**1**	**2**	**3**	**4**	**5**
1	1	0	0	0	0
2	1	0	0	0	0
3	1	0	0	1	0
4	1	0	0	1	0
5	1	0	0	1	0
6	1	0	1	1	0
7	1	1	1	1	0
8	1	1	1	1	0
9	1	1	1	0	0
10	1	1	1	0	0
11	1	1	1	0	0
12	1	1	1	0	0
13	1	1	1	1	1
14	1	1	1	1	1
15	1	1	1	1	1
16	1	1	1	1	1
17	1	1	1	1	0
18	1	1	1	1	0
19	1	1	1	1	0
20	1	1	1	1	0
21	1	1	1	1	0
22	1	1	1	0	0
23	1	1	1	0	0
24	1	0	0	0	0

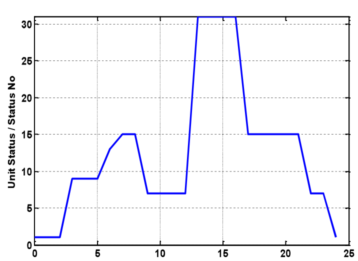

Figure 2: 24-Hour Generation Scheduling Trajectory for 5 Units via CDP

Figure 2 illustrates the path of viable states based on the committed units and optimal total production cost for each feasible state every hour.

4.1.2 Results for Sequential Combination DP (SC-DP)

There is a detailed, high-priority order of the sequence to be followed in creating units. The sequence of units is strictly established by the full load average production cost (FLAPC) associated with each unit. Moreover, the sequence of units has shifted, so Unit 3 is now Unit 2 and vice versa, while the sequence of all other units is unchanged from CDP. The FLAPC delivers the discipline priority flow of 5 units being listed in Table 3. The schedule for five units within a 24 h time horizon is depicted in Table 4, while generator production cost P_{cost} is illustrated in Table 5. Figure 3 depicts the trend of potential states along with hourly generation cost for each state.

Table 2: Production Cost in each Hour for CDP

Hour	P_{cost}	Hour	P_{cost}
1	6394.97	13	17464.3
2	8382.70	14	17725.2
3	9396.77	15	16068.8
4	7378.14	16	17217.4
5	10312.8	17	13591.1
6	11889.2	18	13929.8
7	14950.7	19	16297.8
8	16165.3	20	15376.1
9	12604.1	21	15834.1
10	13111.7	22	12435.3
11	13621.2	23	10925.3
12	12773.1	24	6890.6

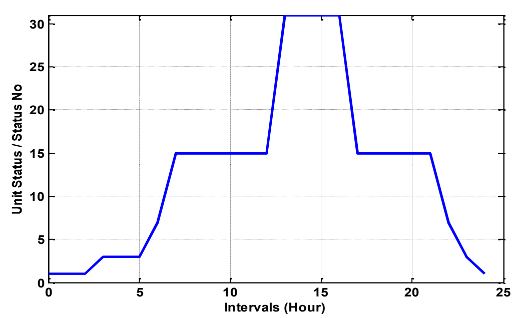

Figure 3: 24-Hour Unit Commitment Trajectory for a 5-Unit System Solved via SC-DP

Table 3: Priority Unit List for 5-Units

Units	1	2	3	4	5
FLAPC	18.39	21.73	21.98	26.89	37.92

4.1.3 Results for Truncation Combination DP (TC-DP)

For this case, all 5 units are required to be in operation to meet the hourly maximum load demand over the 24-hour load period. In the case of, say, a

5-unit system, truncation combination dynamic programming gives results that are nearly identical to the full enumeration DP. Therefore, the selected number of units for TC-DP is 5.

Table 4: UC Schedule Derived from Sequential Combination Dynamic Programming

	Units				
hour	**1**	**2**	**3**	**4**	**5**
1	1	0	0	0	0
2	1	0	0	0	0
3	1	1	0	0	0
4	1	1	0	0	0
5	1	1	0	0	0
6	1	1	1	0	0
7	1	1	1	1	0
8	1	1	1	1	0
9	1	1	1	1	0
10	1	1	1	1	0
11	1	1	1	1	0
12	1	1	1	1	0
13	1	1	1	1	1
14	1	1	1	1	1
15	1	1	1	1	1
16	1	1	1	1	1
17	1	1	1	1	0
18	1	1	1	1	0
19	1	1	1	1	0
20	1	1	1	1	0
21	1	1	1	1	0
22	1	1	1	0	0
23	1	1	0	0	0
24	1	0	0	0	0

Table 5: Generation Cost Distribution Over Scheduling Horizon

Hour	P_{cost}	Hour	P_{cost}
1	6394.97	13	17464.3
2	8382.70	14	17725.2
3	9559.64	15	16068.8
4	7570.93	16	17217.4
5	10227.24	17	13591.19
6	12098.36	18	13929.82
7	14950.7	19	16297.8
8	16165.3	20	15376.1
9	13084.7	21	15834.1
10	13591.1	22	12435.3
11	14099.44	23	10227.24
12	13253.39	24	6890.61

The optimized generation schedule using TC-DP approach is presented in Table 6. The total cost of production over all hours in the time period is shown in Table 7.

Table 6: Optimized Generation Schedule using TC-DP Approach

	Units				
hour	**1**	**2**	**3**	**4**	**5**
1	1	0	0	0	0
2	1	0	0	0	0
3	1	0	0	1	0
4	1	0	0	1	0
5	1	0	0	1	0
6	1	0	1	1	0
7	1	1	1	1	0
8	1	1	1	1	0
9	1	1	1	0	0
10	1	1	1	0	0
11	1	1	1	0	0
12	1	1	1	0	0
13	1	1	1	1	1
14	1	1	1	1	1
15	1	1	1	1	1
16	1	1	1	1	1
17	1	1	1	1	0
18	1	1	1	1	0
19	1	1	1	1	0
20	1	1	1	1	0
21	1	1	1	1	0
22	1	1	1	0	0
23	1	1	1	0	0
24	1	0	0	0	0

Table 7: Hourly Generation Cost Schedule

Hour	P_{cost}	Hour	P_{cost}
1	6394.97	13	17464.3
2	8382.70	14	17725.2
3	9396.77	15	16068.8
4	7378.14	16	17217.4
5	10312.8	17	13591.1
6	11919.3	18	13929.8
7	14950.7	19	16297.8
8	16165.3	20	15376.1
9	12604.1	21	15834.1
10	13111.7	22	12435.3
11	13621.2	23	10925.3
12	12773.1	24	6890.6

The results show that despite having a specific CPU time slower than SC-DP, CDP ends up outperforming TC-DP in slightly higher production cost due to permutation of order of Units 2 & 3 while also exhibiting the least compatibility, thus proving the compatibility of CDP. That is, this cost increment happens in hour 6, which it the costly case as above in CDP where unit 3 is ON and unit 2 is OFF, but the truth is that Unit 3 is actually Unit 2 which is much more expensive than Unit 3. The hourly commitment pattern of 5 Units over 24 hours using TC-DP method illustrated in Figure 4.

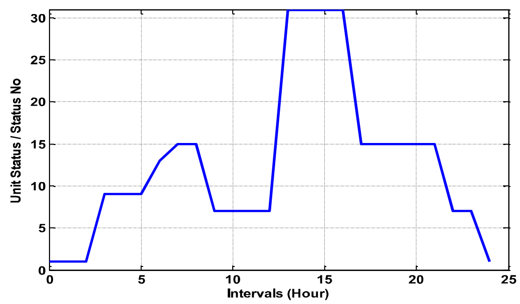

Figure 1: Hourly Commitment Pattern of 5 Units Over 24 Hours Using TC-DP Method

Table 8 shows the total production cost and execution time analysis across various DP techniques considered in this work.

Table 8: Total Production Cost and Execution Time Analysis across DP Techniques

Techniques	Overall Generation Cost ($)	Time of CPU (Sec)
CDP	312,217.38	19.02
SC-DP	313,746.92	5.15
TC-DP	312,247.42	18.75

4.2 Test System 2

In this case, CDP, SC-DP, and TC-DP are used to 10-generator, 24-hour UC schedule, and the results are compared. The data for input and load is provided in [8].

4.2.1 Benchmark Outcomes for Conventional DP (CDP)

According to the full listing of units, the unit scheduling has been presented in Table 9, reflecting the minimum up and down time requirements.

4.2.2 Performance Analysis of SC- DP

In this case, the sequence of units has also been altered, meaning Unit 3 is now designated as Unit 2 according to the strict priority order outlined in Table 10, with all other 8 units maintaining the original order from the unit data. The UC schedule has been determined and is presented in Table 11.

4.2.3 Performance Analysis of TC-DP

Eight units are adequate in this instance to meet the load requirement for every hour within a 24-hour load period. Therefore, 8 units are chosen according to the priority sequence outlined in Table 10, and the schedule for the committed units is presented in Table 12.

Table 9: UC Schedule for CDP

	Units									
hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	1	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0
4	1	1	0	1	0	0	0	0	0	0
5	1	1	0	1	0	0	0	0	0	0
6	1	1	0	1	1	0	0	0	0	0
7	1	1	0	1	1	0	0	0	0	0
8	1	1	0	1	1	0	0	0	0	0
9	1	1	1	1	1	1	0	0	0	0
10	1	1	1	1	1	1	0	0	0	0
11	1	1	1	1	1	1	0	1	0	0
12	1	1	1	1	1	1	0	1	1	0
13	1	1	1	0	1	1	1	0	1	0
14	1	1	0	0	1	1	1	1	1	0
15	1	1	0	0	1	1	1	0	0	0
16	1	1	0	0	1	0	0	0	0	0
17	1	1	0	0	1	0	0	0	0	0
18	1	1	0	1	1	0	0	0	0	0
19	1	1	1	1	1	0	0	0	0	0
20	1	1	1	1	1	1	1	1	0	0
21	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	1	0
24	1	1	0	0	0	0	0	0	1	0

Table 10: Priority Unit List for 10-Units

Units	**1**	**2**	**3**	**4**	**5**
FLAPC	18.39	19.39	21.73	21.98	22.48
Units	**6**	**7**	**8**	**9**	**10**
FLAPC	26.89	33.39	37.92	39.36	39.97

Table 11: UC Schedule for SC-DP

	Units									
hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	1	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0
4	1	1	1	0	0	0	0	0	0	0
5	1	1	1	0	0	0	0	0	0	0
6	1	1	1	1	0	0	0	0	0	0
7	1	1	1	1	0	0	0	0	0	0
8	1	1	1	1	1	0	0	0	0	0
9	1	1	1	1	1	0	0	0	0	0
10	1	1	1	1	1	1	0	0	0	0
11	1	1	1	1	1	1	1	0	0	0
12	1	1	1	1	1	1	1	1	0	0
13	1	1	1	1	1	1	1	1	0	0
14	1	1	1	1	1	1	1	0	0	0
15	1	1	1	1	1	0	0	0	0	0
16	1	1	1	1	1	0	0	0	0	0

17	1	1	1	1	1	0	0	0	0	0
18	1	1	1	1	1	0	0	0	0	0
19	1	1	1	1	1	0	0	0	0	0
20	1	1	1	1	1	1	1	1	0	0
21	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	1	0
24	1	1	0	0	0	0	0	0	0	0

Table 12: Unit Commitment Results for Thermal System via TC-DP

	Units							
hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	1	1	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0
4	1	1	0	1	0	0	0	0
5	1	1	0	1	0	0	0	0
6	1	1	1	1	0	0	0	0
7	1	1	1	1	0	0	0	0
8	1	1	1	1	1	0	0	0
9	1	1	1	1	1	0	0	0
10	1	1	1	1	1	1	1	0
11	1	1	1	1	1	1	1	0
12	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1
14	1	1	0	1	1	1	1	0
15	1	1	0	1	1	0	0	0
16	1	1	0	1	1	0	0	0
17	1	1	0	1	1	0	0	0
18	1	1	0	1	1	0	0	0
19	1	1	1	1	1	0	1	0
20	1	1	1	1	1	0	1	1
21	1	1	1	1	1	0	1	1
22	1	1	1	1	1	0	1	0
23	1	1	1	0	0	0	0	0
24	1	1	0	0	0	0	0	1

Performance comparison between overall production cost obtained by different DP to other methods from literature is represented in Table 13. We observe that CDP takes significantly more CPU time and has a higher total production cost than both SC-DP and TC-DP. Because optimum units are chosen through TC-DP to meet the load based on FLAPC, followed by a complete enumeration of only those units, TC-DP reduces the computation requirement and search space.

Table 13: Cost and CPU Time Evaluation of Scheduling Techniques for 10-Unit Dispatch

Methods	**Overall Production Cost ($)**	**CPU Time (sec)**
LRGA [14]	564,800	518
EPL [15]	563,977	0.72
HSA [16]	565,827	79
MAEP-PL [17]	564,073	1.63
RCGA [18]	563,937	-
CZOA [19]	563,428	-
CDP	572,368.47	946.38
SC-DP	576,759.64	9.69
TC-DP	**561,116.60**	**222.30**

5. CONCLUSION

Optimal Unit Commitment (UC) of thermal systems yields an economic benefit for electric utilities. UC has been formulated and the solution is obtained using some classical frameworks, such as DP, SC-DP and TC-DP. These algorithms were tested on five units and ten unit's systems for the total operating cost and CPU time. We show that solutions delivered by conventional DP are optimal for smaller systems, however as the size of the system grows larger, it no longer yields the best results, and the run time is exponential. Nevertheless, TC-DP provides the best accuracy and time efficiency results when considering larger systems as compared to most existing CDP, SC-DP models in literature.

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