Solving Unit Commitment Problem in Deregulated Power Systems Environment

حل مشكله جدولة وحدات التوليد فى نظم القوى المهيكلة

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الملخص:

مع التغيرالتكنولوجي سريع الخطى في صناعة الطاقة، والربط بين الدول وبعضها فى شبكات الطاقه الكهربيه تحول سوق الطاقه الكهربيه من سوق مركزى الى سوق مهيكل يعتمد على التعاقدات . لذا فان مشكله جدوله الوحدات التى تعرف على انها ايجاد جدول او خريطه تشغيل لوحدات التوليد لتحقيق اقل تكلفه تشغيل مع الوفاء بالحمل المطلوب تظهر ايضا بقوه فى السوق التنافسى المعتمد على التعاقدات الثنائيه والمتعدده الاطراف. فى هذه البيئه الجديده لابد من تحقيق قيود مشكله التزام الوحدات التقليديه بالاضافه الى قيود جديده تعتمد على طبيعه تلك البيئه منها الالتزام بالتعاقدات المبرمه بين الاطراف وتغير داله الهدف من تقليل تكلفه التشغيل للوحدات الى تحقيق اقصى ربح ممكن لوحدات التوليد ونتيجه لهذه التغيرات فان المشكله تزداد تعقيدا وخصوصا عند زياده عدد الوحدات .فى هذا البحث يتم تناول مشكله جدوله الوحدات التقليديه وايضا فى نظم القوى المهيكله وتم بناء خوارزم رياضى يسمى "البرمجة الديناميكية" فى بيئه ماتلاب لحل المشكله قيد الدراسة .

ABSTRACT:

With the fast-paced changing technologies in the power industry, new power references addressing new technologies are coming to the market. So there is an urgent need to keep track of international experiences and activities taking place in the field of modern unit-commitment (UC) problem. UC is a nonlinear mixed integer optimization problem to schedule the operation of the generating units at minimum operating cost while satisfying the demand and other equality and inequality constrains. The UC problem has to determine the on/off state of the generating units at each hour of the planning period and optimally dispatch the load among the committed units. UC is the most significant optimization task in the operation of the power systems. Solving the UC problem for large power systems is computationally expensive. The complexity of the UC problems grows exponentially with the number of generating units especially by applying the deregulated rules in power system. Where in this environment the objective function is maximizing the profit while satisfying the regular unit commitment constrains in addition to new constrains such as bilateral and multilateral contracts. So in this paper, an exact mathematical optimization procedure called “*dynamic programming.*” is presented to solve of the UC problem in the deregulated environment. The proposed algorithm is implemented in MATLAB environment.

Keywords— dynamic programming, (DP), unit commitment, deregulation, generation companies (GENCOs), Independent System Operator (ISO), market clearing price(MCP), optimization methods, power generation dispatch.

1. NOMENCLATURE

$F(P_{it})$ Production cost of unit i in time period t ($).
SUC_{it} Start-up cost for unit i in time period t ($).
TC Total cost of GENCO ($).
CH_i Cold start hour (hr) at unit i.

CSC_i	Cold start-up cost for unit *i*, ($).
HSC_i	Hot start-up cost for unit *i*, ($).
$D_t^{'}$	Forecasted demand at hour t, MW.
N	Number of generator units.
Nt	A chosen number of intervals.
$P_{i\min}$	Minimum limit of generator i, MW.
P_{it}	Power generation of unit i at hour t, MW.
$P_{i\max}$	Maximum limit of generator *i* ,MW.
R_{it}	Reserve generation of unit *i* at hour ,*t* MW.
SDC_{it}	Shut-down cost of unit *i* at time period *t*, ($).
SP_t	Forecasted spot price at hour *t*,($).
$SR_t^{'}$	Forecasted reserve at hour *t*,MW.
T	Number of hours.
$\mathrm{T_i^{off}}$	Minimum off-time of unit *i* (hr).
$\mathrm{T_i^{on}}$	Minimum-on time of unit *i* (hr).
$\mathrm{U_{it}}$	On/off status of generator i athour t.
$\mathrm{X^{on}_{(i,t-1)}}$	Time duration for which unit *i* has been on-time at hour *t* (hr).
$\mathrm{X^{off}_{(i,t-1)}}$	Time duration for which unit *i* has been off-time at hour *t* (hr).
RP_t	Forecasted reserve price at hour *t*.
r	Probability that the reserve is called and generated.
PF	Profit of GENCO ($).
RV	Revenue of GENCO ($).
$x_{k,t}$	Specifies the consecutive time that the unit has been on (+) or off (-) at the end of the hour *t*.
$\mathrm{S_k}(x_{k,t})$	Start-up cost, which for thermal Units depends on the prevailing temperature of the boilers .
K	*Represent the generator number*
$P_k^{\max}$	Maximum output of generator k
$P_k^{\min}$	Minimum output of generator k
t_k^{dn}	the time that generator should be stay off when shutdown.
t_k^{up}	The time that generator should be stay on when start up.

2. INTRODUCTION

The regular unit Commitment is the problem of determining the schedule of generating units. Besides achieving the minimum total production cost, generation schedule needs to satisfy a number of operating constraints. These constraints reduce freedom in the choice of starting up and shutting down generating units [1]. The constraints to be satisfied are usually the status restriction of individual generating units, minimum up time, minimum down time, capacity limits, generation limit for the first and last hour, limited ramp rate, group constraint, power balance constraint, spinning reserve constraint, and etc. The high dimensionality and combinatorial nature of the UC problem curtails the attempts to develop any rigorous mathematical optimization method capable of solving the whole problem for any real-size system. Different approaches include priority list (PL), integer/mixed-integer programming method, dynamic programming (DP), branch and bound method, and Lagrangian relaxation (LR). PL[2-3] is the simplest and fastest but achieves a poor final solution. The LR method [4] provides a faster solution but it suffers from numerical convergence [5] and existence of duality gap. The integer [6] and mixed-integer [7] methods adopt linear programming to solve and check for an integer solution. These methods fail when the number of units increases because they require a large memory and suffer from great computational delay. The branch-and bound method [8] employs a linear function to represent fuel cost and start-up cost and obtains a lower and upper bounds. The deficiency of this method is the exponential growth in the execution time for systems of a practical size [9] recently particle swarm optimization (PSO), genetic algorithm (GA),tabu search, ant colony (ACO) are used in solving UCP. The UC problem has been earlier solved by enumerating all possible combinations of the generating units and then the combinations that yields the least cost of operation are chosen as the optimal solution. Even though the method was not suitable for a large size electric utility, it was capable of providing an accurate solution. The main objective of UCP is to minimize the system production cost during the period while simultaneously satisfying the load demand, spinning reserve, ramp constraints and the operational constraints of the individual unit. To achieve an accurate UC schedule for either utilities or companies with more number of generating units and unpredicted market behavior becomes a challenge for the researchers in the recent times. There are a number of factors that affect the economic decisions of power generators. These include operating and maintenance costs, output control, start-up costs and emission caps etc. in addition to these, appropriate dispatch of generators also based upon the physical characteristics and limitations of the plant. These can include ramp-up rates, ramp- down rates and minimum and maximum run times. Unit commitment is an operation scheduling function that covers the scope of hourly power system operation decisions with a one-day to one week horizon. Scheduling the on and off times of the generating units and minimizing the cost for the hourly generation schedule is the economics to save great deal of money by turning units off (decommiting) when they are not needed. By incorporating UC schedule, the electric utilities may save millions of Dollars per year in the production cost.

3. DYNAMIC PROGRAMMING ALGORITHM

There are several approaches to implement an optimization procedure. One approach is an exact mathematical optimization procedure called “*dynamic programming.*” In mathematics and computer science, dynamic programming is a method of solving problems that exhibit the properties of overlapping sub problems and optimal substructure. The method takes much less time than naive methods. The term was originally used in the 1940s by Richard Bellman to describe the process of solving problems where one needs to find the best decisions one after another. By 1953, he had refined this to the modern meaning. The field was founded as a systems analysis and engineering topic that is recognized by the IEEE. Bellman's contribution is remembered in the name of the Bellman equation, a central result of dynamic programming which restates an optimization problem in recursive form. A Bellman equation (also known as a dynamic programming equation), named after its discoverer, Richard Bellman, is a necessary condition for optimality associated with the mathematical optimization method known as dynamic programming. The word "*programming*" in "*dynamic programming*" has no particular connection to computer programming at all, and instead comes from the term "mathematical programming", a synonym for optimization. Thus, the "program" is the optimal plan for action that is produced. For instance, a finalized schedule of events at an exhibition is sometimes called a program. Optimal substructure means that optimal solutions of sub problems can be used to find the optimal solutions of the overall problem. For example, the shortest path to a goal from a vertex in a graph can be found by first computing the shortest path to the goal from all adjacent vertices, and then using this to pick the best overall path, as shown in Figure.1 .In general, we can solve a problem with optimal substructure using a three-step process:

1. Break the problem into smaller sub problems.
2. Solve these problems optimally using this three-step process recursively.
3. Use these optimal solutions to construct an optimal solution for the original problem.

The sub problems are, themselves, solved by dividing them into sub-sub problems, and so on, until we reach some simple case that is solvable in constant time.

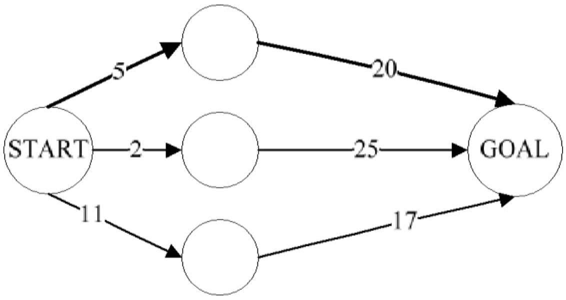

Fig. 1 Finding the shortest path in a graph using optimal substructure

3.1 Dynamic Programming Approaches

There are two approaches generally used for dynamic programming namely; top-down approach and bottom-up approach as explained in the following subsections.

A) Top-Down Approach

The problem is broken into sub problems, and these sub problems are solved and the solutions remembered, in case they need to be solved again. This is recursion and memorization combined together.

B) Bottom-Up Approach

All sub problems that might be needed are solved in advance and then used to build up solutions to larger problems. This approach is slightly better in stack space and number of function calls, but it is sometimes not intuitive to figure out all the sub problems needed for solving the given problem.

3.2 Example on Deterministic Finite-State Problems

Scheduling problem: Find optimal sequence of operations A, B, C, D.A must precede B, and C must precede D, in Fig .2 given start up cost *SA* and *SC*, in Fig .3 and setup transition cost *Cmn* from operation *m* to operation *n*

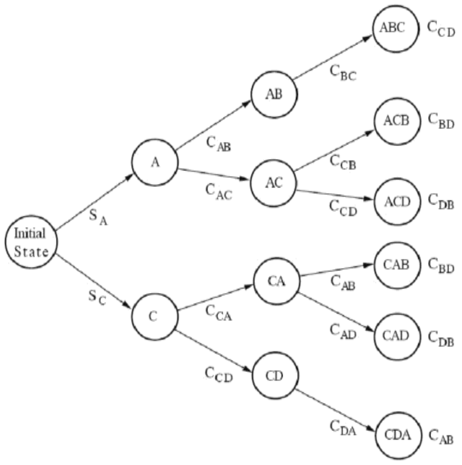

Fig .2 Optimal sequences of operations

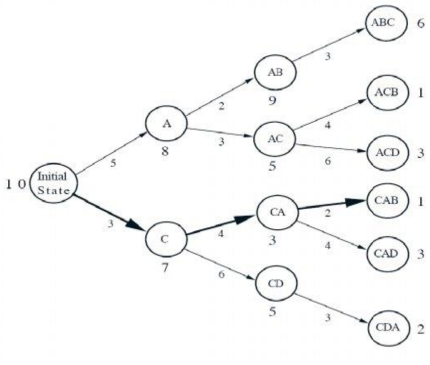

Fig .3 Represent a unit shipment cost

This is one dimension problem which represents a unit shipment cost, the value in the arc is the cost and the node represents the states.

1. State 1= min (5,3) = 3
   Selection of state 1=C
   Solution of state 1= initial state to C
2. State 2= state 1+min(4,6)=3+4
   Selection of state2=CA
   Solution of state 2= initial state - C - CA
3. State 3= state2+min(2,4)=7+2=9
   Selection of state 3=CAB

Solution of the state 3= initial state - C - CA-CAB. Final solution is(initial state - C - CA-CAB.) .The minimum cost is= 3+4+2=9.

4. UC PROBLEM FORMULATION

In this section, the formulation of the UC problem for both the regulated and deregulated environment is listed and highlights differences between them.

a) UC in Regulated Power System

The objective of the UC problem is to minimize the total operating costs subjected to a set of system and unit constraints over the scheduling horizon as shown in fig.4. .

$$TC = \sum_{i}^{N}\sum_{t}^{T} .F(P_{it})\mathrm{U}_{\mathrm{it}} + SUC_{it}.(1-\mathrm{U}_{\mathrm{it}}).\mathrm{U}_{\mathrm{it}} + SDC_{it}.(1-\mathrm{U}_{\mathrm{it}}).\mathrm{U}_{\mathrm{i,(t-1)}} \quad (1)$$

The generator fuel-cost function can be expressed as:

$$F(P_{it}) = a_i + b_i.P_{it} + c_i.P_{it}^2 \quad (2)$$

Where, a_i, b_i and c_i are the unit cost coefficients.

Subject to:

1) Demand Constraint:

$$\sum_{i=1}^{N} P_{it}U_{it} \le D_t' \qquad \text{t=1,…, T} \qquad (3)$$

2) Reserve Constraint:

$$\sum_{i=1}^{N} R_{it}U_{it} \le SR_t' \qquad \text{t=1,…, T} \qquad (4)$$

.

3) Power generation and reserve limits:

$$P_{i\min} \le P_{(i,t)} \le P_{i\max} \quad \text{i=1,…,N} \qquad (5)$$

$$0 \le R_{(i,t)} \le P_{i\max} - P_{i\min} \quad \text{i=1,…,N} \qquad (6)$$

4) Minimum Up and Down time Constraints:

$$[\mathrm{X}^{\mathrm{on}}_{(\mathrm{i,\,t-1})} - \mathrm{T}^{\mathrm{on}}_{\mathrm{i}}][\mathrm{U}_{(\mathrm{i,\,t-1})} - \mathrm{U}_{\mathrm{it}}] \ge 0 \quad (7)$$

$$[\mathrm{X}^{\mathrm{off}}_{(\mathrm{i,\,t-1})} - \mathrm{T}^{\mathrm{off}}_{\mathrm{i}}][\mathrm{U}_{\mathrm{it}} - \mathrm{U}_{(\mathrm{i,\,t-1})}] \ge 0 \quad (8)$$

Start-up cost is calculated from (9) .

$$SUC_{it} = \begin{cases} \mathrm{HSC}_{\mathrm{i}},\ \mathrm{X}^{\mathrm{off}}_{(\mathrm{i,\,t-1})} \le \mathrm{T}^{\mathrm{off}}_{\mathrm{i}} + CH_i \\ CSC_i,\ \mathrm{X}^{\mathrm{off}}_{(\mathrm{i,\,t-1})} > \mathrm{T}^{\mathrm{off}}_{\mathrm{i}} + CH_i \end{cases} \quad (9)$$

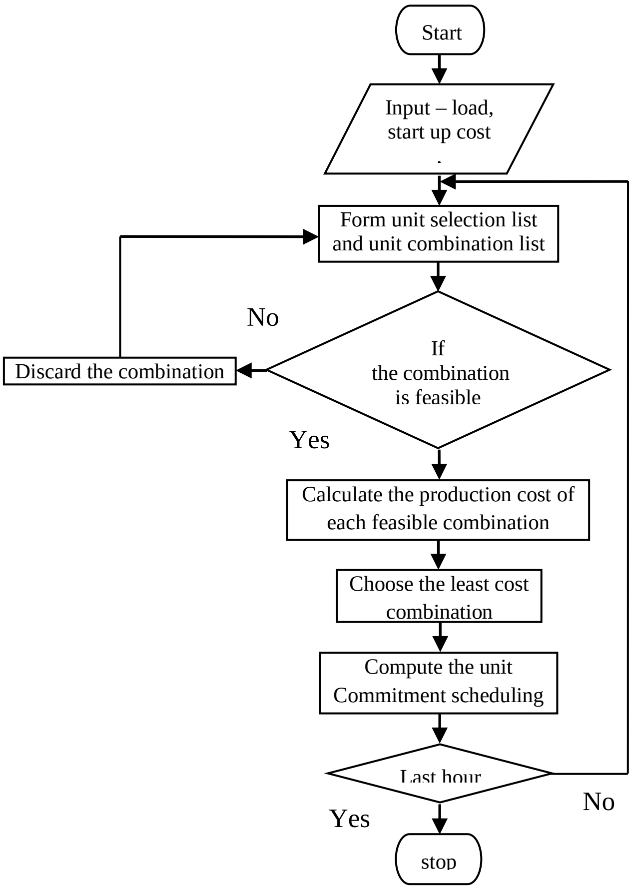

Fig. 4 Flow chart to solve unit commitment problem

b) UC in Deregulated Power System

Deregulation in power sector increases the efficiency of electricity production and distribution, offer lower prices, higher quality, a secure and a more reliable product and this affect UC problem. UC schedule depends on the market price in the deregulated market. In deregulated environment utilities are not required to meet the demand. GENCO can consider a schedule that produce less than the predicted load demand and reserve but creates maxi- mum profit. More number of units are committed when the market price is higher. When more number of generating units are brought online more power is generated and participated in the deregulated market to get maximum profit. The commitment decisions are made by the Independent System Operator (ISO). The ISO resembles very much the operation of a power generating utility under regulation. The ISO manages the transmission grid, controls the dispatch of generation, oversees the reliability of the system, and administers congestion protocols [10-12]. The ISO is a non-profit organization. Its economic objective is to maximize social welfare, which is obtained by minimizing the costs of reliably supplying the aggregate load. Under deregulation, the UCP for an electric power producer will require a new formulation that includes the electricity market in the model as shown in fig .5 where lrg.cons and sml.cons means large and small consumers respectively. Starting from the late eighties, the transition towards the wholesale electric energy market, taking place in most countries in the world, demanded for a reconsideration of the UCP. As deregulation is being implemented in various regions of the world, the traditional UCP continues to remain applicable for the commitment decisions made by ISO [13].

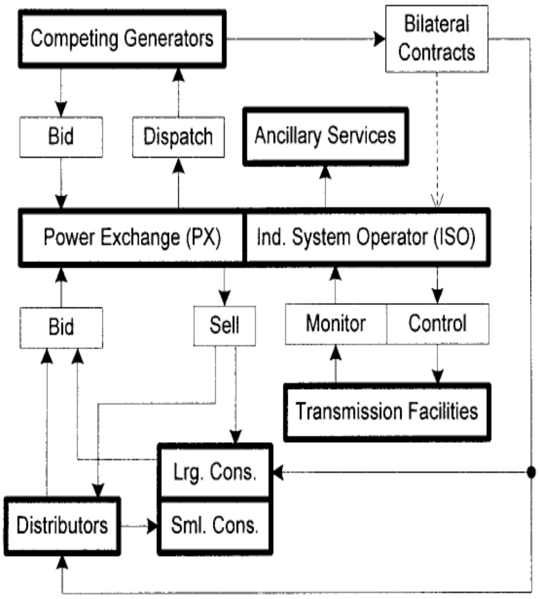

Fig. 5 Basic structure of deregulated electricity market

In fact, generation companies (GENCOs), operating in an open electricity market, are no longer bound to serve a local load, but aim at maximizing their own profits. In the pool-based electricity market, every GENCO submits bidding price function to the ISO for every hour of the planning horizon. The ISO uses bidding price function and forecasted demand to determine market clearing price (MCP) and hourly generation outputs by maximizing the total surplus of generators and consumers. In the market, ISO would be forecasting the demand and the price for the next day/hour. The GENCOs will send its bidding to the ISO, depending upon the demand and its generator coefficients. The ISO will accept and select the bidder whose price is less than or equal to its expected price (forecasted price). If the bidder's price is more than the forecasted one, then ISO will fix the forecasted price as MCP. If any of the GENCOs fix the price below the forecasted price, then the ISO will fix the lowest price as the MCP. However, each company's bidding differs from others, depending upon their generator coefficient which is confidential [14] and therefore ISO has to be very judicious for the equal participation of all GENCOs in the competing pool.

Generally the maximization of profit is different from minimizing cost because GENCOs no longer have the obligation to serve. They may choose to generate less than the demand, which allows more flexibility in UC schedules. However, in certain markets such as New Zealand Energy Market, UC is the sole responsibility of individual GENCOs. In these markets the GENCOs use their bidding strategies and submit single part bids to the ISO, for fully satisfying the forecasted load without any flexibility [15]. These GENCOs in advance ensure that optimal dispatch for the forecasted price, while submitting their bids. Hence, the information on optimal production obtained, is still valuable when making bidding strategies. These strategies may however include uncertainty in price, the behavior of other participants and risk averseness, of the GENCOs. Therefore a cumulative bid for all units owned by GENCOs may also be submitted to the pool. Therefore, ISO will look vigilantly into both single part bid and cumulative bid, before making the MCP, in case of uncertainties. But only after the market is cleared, each GENCO would know their individual demand in the spot market. Now, based on these demands, the GENCOs can again carryout self-commitment to obtain optimal decisions. This is when the demand constraints become relevant for competitive GENCOs. This makes the UC similar to the traditional power systems where the objective is to minimize system cost to meet system demand.

Considering the Singapore market, the GENCOs will participate in the market operations and submit their biddings depending upon the forecasted load and price, by the market operator. The whole-sale spot market prices, reflect the least-cost market solution to the dispatch of energy and the provision of reserve and regulation. In general, this means that each generator that submits an offer below the market price will be dispatched and a generator that submits an offer above the market price will not be dispatched. The market price for energy that dispatchable generators receive is a nodal price, which may vary according to the location on the network of the node, to which the dispatchable generator has been assigned [16]. The important role of the wholesale electricity market is to determine the competitive electricity prices for the benefit of consumers, in the contestable market. Therefore, each generator competes to bid below or at least equal to the forecasted price, so that the unit should not incur a loss and may choose to generate less than the demand.

According to this, the GENCOs will dispatch the load in an hour if they get the profit in that hour. Each generator that participates in the markets or that causes or permits electricity to be conveyed into, through or out of the ISO-controlled grid, shall operate and maintain its generation facilities and equipment in a manner that is consistent with the reliable operation of the ISO-controlled grid. They shall assist the ISO in the discharge of its responsibilities related to reliability. Based on the above mentioned activities of GENCOs.

UC choices are therefore driven by the expected behavior of market prices over the time rather than by the forecasted load levels. A number of technical papers witness the renewed interest in the UC problem with the aim of developing optimal bidding strategies for the market [17 - 30].The objective function is given by the sum over the hours in the interval $[0,T]$ of the revenue minus the cost. The revenue is obtained from supplying the bilateral contracts and by selling to the power pool at a price of m_t per MWH the surplus energy E_t (if any) produced in each hour t. The cost includes the cost of producing the energy, buying shortfalls (if needed) from the power pool, and the startup costs. Defining the supply amount stipulated under the bilateral contract by l_t (MWH) and by R (\$/MWH) the price, the objective function (maximum total profit) is given by

$$Max\, PF = RV - TC \tag{10}$$

$$\mathbf{CF_k(\boldsymbol{p}) = \boldsymbol{a_k} + \boldsymbol{b_k p} + \boldsymbol{c_k p^2}} \tag{11}$$

$$\underset{v_{k,t},P_{k,t},E_t}{\mathrm{Max}} \left\{ \sum_{t=1}^{T} \{ l_t R - m_t E_t - \sum_{k=1}^{M} [\mathrm{CF_k}(P_{k,t}) + S_k(x_{k,t})(1 - v_{k,t-1})] v_{k,t} \} \right\} \tag{12}$$

A positive value of E_t indicates that E_t megawatts hour are bought from the power pool and a negative value indicates that $-E_t$ megawatts hour are sold to the pool. Since the quantity $l_t R$ is a constant, the optimization problem reduces to:

$$\underset{v_{k,t},P_{k,t},E_t}{\mathrm{Max}} \left\{ \sum_{t=1}^{T} \{ -m_t E_t - \sum_{k=1}^{M} [\mathrm{CF_k}(P_{k,t}) + S_k(x_{k,t})(1 - v_{k,t-1})] v_{k,t} \} \right\} \tag{13}$$

Subject to the following constraints
(for t=1,…,T and k=1,…,M)

Load:

$$E_t + \sum_{k=1}^{M} v_{k,t} P_{k,t} = l_t \tag{14}$$

Capacity limits:

$$v_{k,t} P_k^{\min} \le P_{k,t} \le v_{k,t} P_k^{\max} \quad (15)$$

Minimum down time:

$$v_{k,t} \le 1 - \mathrm{I}(-t_k^{dn} + 1 \le x_{k,t-1} \le -1) \quad (16)$$

Minimum up time:

$$v_{k,t} \ge \mathrm{I}(1 \le x_{k,t-1} \le t_k^{up} - 1) \quad (17)$$

where $\mathrm{I}(x) = \begin{cases} 0 & \text{if } x \text{ is false} \\ 1 & \text{if } x \text{ is true} \end{cases}$

$P_{k,t} \ge 0$ and E_t unrestricted in sign $v_{k,t} = \{0,1\}$

After substituting in the objective function the value of $E_t = l_t - \sum_{k=1}^{M} v_{k,t} P_{k,t}$, obtained from Equation (14), we re-write Equation 16 as follows:

$$\underset{v_{k,t},P_{k,t},E_t}{\mathrm{Max}} \left\{ \sum_{t=1}^{T} \{-m_t[l_t - \sum_{k=1}^{M} P_{k,t} v_{k,t}] - \sum_{k=1}^{M} [\mathrm{CF}_\mathrm{k}(P_{k,t}) + S_k(x_{k,t})(1 - v_{k,t-1})] v_{k,t} \} \right\} \quad (18)$$

which after removing constant terms is equivalent to:

$$\underset{v_{k,t},P_{k,t}}{\mathrm{Max}} \left\{ \sum_{t=1}^{T} \{ \sum_{k=1}^{M} [m_t P_{k,t} \text{ - } \mathrm{CF}_\mathrm{k}(P_{k,t}) + S_k(x_{k,t})(1 - v_{k,t-1})] v_{k,t} \} \right\} \quad (19)$$

subject to the operating constraints. Because the constraints (14) to (17) refer to individual units only, the advantage of Equation (19) is that the objective function is now separable by individual units. The optimal solution can be found by solving *M* de-coupled sub-problems. Thus, the sub-problem $\mathrm{D_k}$ for the *k*th unit (*k*=1,..,*M*) is.

$$\underset{v_{k,t},P_{k,t}}{\mathrm{Max}} \left\{ \sum_{t=1}^{T} \left[m_t P_{k,t} \text{ - } \mathrm{CF}_\mathrm{k}(P_{k,t}) + S_k(x_{k,t})(1 - v_{k,t-1}) \right] v_{k,t} \right\} \quad (20)$$

5. CASE STUDIES

In this paper there are two case studies which are 3- unit system and 10-unit system .Both cases are tested for regulated and deregulated UC.

5.1. Case 1: 3-Unit System

The system data for this case is listed in Table 1 and the load curve is shown in Fig. 6 .The 3-units 12-hours system has a total capacity of 1200 MW and peak load and minimum load of 1100 MW and 170 MW, respectively [31].

Table 1: Cost Coefficients, Unit Characteristics of 3-units system

Ge No	Max MW	Min. MW	a_k	b_k	c_k	Min Up Time (Hr)	Min Down Time (Hr)	Shut down Cost ($)	Cold Start (Hr)	Init. Unit status	Startup costs Hot ($)	Startup costs Cold ($)
1	600	100	0.002	10	500	4	2	50	4	-5	70	176
2	400	100	0.0025	08	300	5	3	60	5	8	74	187
3	200	50	0.005	06	100	5	1	30	5	8	50	113

This data has been taken from [31] and Washington university website this is a reference case for testing our matlab code and represent the small number of generation units in next section the other case results show the behavior of the proposed method for large number of generation units.

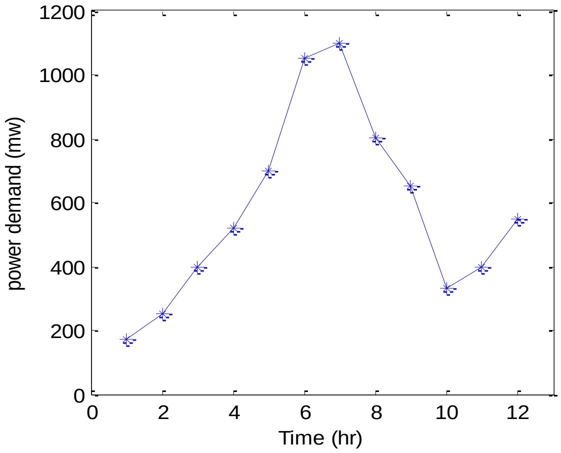

Fig. 6. Load curve of 3 units system

The listed data above is used as input to the UC MATLAP program in the regulated environment and the output is listed in Table 2. While the unit's production cost in the deregulated environment is listed in Table 3.

Table 2 UC schedule of 3 – unit 12-hour system (regular UC)

hour	Demand	U 1	U2	U3	cost($)
Initial state		0	1	1	
1	170	0	1	1	1670
2	250	0	1	1	3908
3	400	0	1	1	7408
4	520	0	1	1	12024
5	700	1	1	1	19394
6	1050	1	1	1	30199
7	1100	1	1	1	41599
8	800	1	1	1	49579
9	650	1	1	1	56005
10	330	1	1	1	59615
11	400	1	1	1	63760
12	550	1	1	1	69236

Fig. 7 shows the different values of the revenue, cost and profit at various operating hours. In this figure, the profit of GENCO, which is the different between the revenue and generation costs, has a highest value at hr 7 because the load demand is taken from only two units (as show in Table 1) that have low start-up costs, which leads to increase the revenue of GENCO, while the generation costs are remained fixed and the spot price is increased.

Table 3: Unit’s Production for the 3-Unit system (regulated)

Hr	Load	U1	U2	U 3	Fuel Cost$	Tr cost$
1	170	0	100	70	1670	0
2	250	0	100	150	2238	0
3	400	0	200	200	3500	0
4	520	0	320	200	4616	0
5	700	100	400	200	6920	450
6	1050	450	400	200	10805	0
7	1100	500	400	200	11400	0
8	800	200	400	200	7980	0
9	650	100	350	200	6426	0
10	330	100	100	130	3610	0
11	400	100	100	200	4145	0
12	550	100	250	200	5476	0

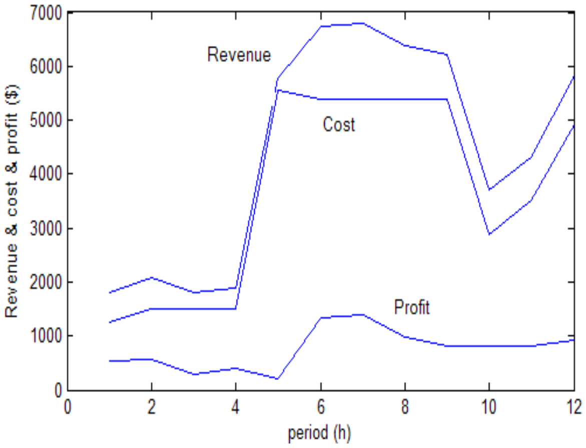

Fig. 7: Revenue, generation costs and profit of GENCO for 3-unit system (deregulated)

To prove the importance of performing a special unit commitment that maximizes the profit in the deregulated environment, a comparison between the profit obtained from performing the regular UC and the corresponding profit obtained from the profit-based UC is held. The result of this comparison is shown in Table 4.

Table 4 Power and reserve generation for 3-unit test system (Comparison between regular and profit-based methods)

	Traditional Unit Commitment					Profit-based Unit Commitment					
Hour	Unit 1	Unit 2	Unit 3	Cost ($)	Profit ($)	Unit 1	Unit 2	Unit 3	Reserve (MW)	Cost ($)	Profit ($)
1	0	100/0	70/20	1671	131.9	0	0	170/20	20	1265.3	537.7
2	0	100/0	150/25	2240	359.6	0	0	200/0	0	1500	570
3	0	200/40	200/0	3502	114.3	0	0	200/0	0	1500	300
4	0	320/55	200/0	4619	318.6	0	0	200/0	0	1500	390
5	100/70	400/0	200/0	7374	-342.3	0	330/70	200/0	70	5115.8	215.7
6	450/95	400/0	200/0	10811	1049.5	0	400/0	200/0	0	5400	1350
7	500/100	400/0	200/0	11406	1074.5	0	400/0	200/0	0	5400	1380
8	200/80	400/0	200/0	7984	573.8	0	400/0	200/0	0	5400	990
9	100/15	350/50	200/0	6432	325.5	0	387.2/12.2	200/0	12.2	5273.1	810
10	100/0	100/0	130/35	3614	99.4	0	130/35	200/0	35	2883.8	829.8
11	100/0	100/40	200/0	4149	170.4	0	200/40	200/0	40	3501.8	817.4
12	100	250/55	200	5482	374.4	0	350/50	200/0	50	4908.4	945
Total				69283	4249.6					43248	9136

5.2 Case 2: 10-Unit, 24-hour System

The data for this case are listed in Table 5 and the load curve of this case is shown in figure 8 this system has a total capacity of 1662 MW and peak and minimum load of 1500 and 700 MW, respectively [32].

Table 5 Cost Coefficients, Unit Characteristics of 10-units system

Gen No	Max MW	Min. MW	$a_{k}10^{-5}$	b_k	c_k	Min Up Time (H)	Min Down Time (H)	Cold Start (Hr)	Init. unit status	Startup costs	
										Hot ($)	Cold ($)
1	455	150	48	16.19	1000	8	8	5	8	4500	9000
2	455	150	31	17.26	970	8	8	5	8	5000	10,000
3	130	20	20	16.6	700	5	5	4	-5	550	1100
4	130	20	211	16.5	680	5	5	4	-5	560	1120
5	162	25	398	19.7	450	6	6	4	-6	900	1800
6	80	20	712	22.26	370	3	3	2	-3	170	340
7	85	25	79	27.74	480	3	3	2	-3	260	520
8	55	10	413	25,29	660	1	1	0	-1	30	60
9	55	10	222	27.27	665	1	1	0	-1	30	60
10	55	10	173	27.79	670	1	1	0	-1	30	60

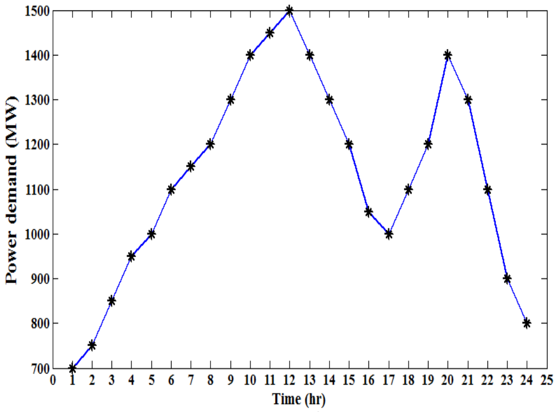

Fig. 8 Load curve of 10 units system

After applying the regular unit commitment algorithm for this system, Table 6 represents the schedule of the 10-units. Also Table 7 represents the production power for the same system. Also, the profit-based UC result for this system is listed in Table 8. Fig. 9 indicate the revenue, generation cost and the profit for the 10-unit test system during the PBUC.

Table 6 UC schedule of 10 – units 24-hours system for regular UC

Hr	D(MW)	Unit Number										Cumulative Cost($/hr)
		1	2	3	4	5	6	7	8	9	10	
Initial state		1	1	0	0	0	0	0	0	0	0	
1	700	1	1	0	0	0	0	0	0	0	0	13.683.13
2	750	1	1	0	0	0	0	0	0	0	0	28237.63
3	850	1	1	0	0	1	0	0	0	0	0	45947.08
4	950	1	1	0	0	1	0	0	0	0	0	64544.75
5	1000	1	1	0	1	1	0	0	0	0	0	85124.76
6	1100	1	1	1	1	1	0	0	0	0	0	108611.8
7	1150	1	1	1	1	1	0	0	0	0	0	131873.8
8	1200	1	1	1	1	1	0	0	0	0	0	156024.1
9	1300	1	1	1	1	1	1	1	0	0	0	184135.2
10	1400	1	1	1	1	1	1	1	1	0	0	214252.7
11	1450	1	1	1	1	1	1	1	1	1	0	246228.8
12	1500	1	1	1	1	1	1	1	1	1	1	280179
13	1400	1	1	1	1	1	1	1	1	0	0	310236.5
14	1300	1	1	1	1	1	1	1	0	0	0	337487.6
15	1200	1	1	1	1	1	0	0	0	0	0	361637.9
16	1050	1	1	1	1	1	0	0	0	0	0	383151.6
17	1000	1	1	1	1	1	0	0	0	0	0	403793.4
18	1100	1	1	1	1	1	0	0	0	0	0	426180.4
19	1200	1	1	1	1	1	0	0	0	0	0	450330.8
20	1400	1	1	1	1	1	1	1	1	0	0	480878.3
21	1300	1	1	1	1	1	1	1	0	0	0	508129.4
22	1100	1	1	0	0	1	1	1	0	0	0	530864.9
23	900	1	1	0	0	0	1	0	0	0	0	548510.3
24	800	1	1	0	0	0	0	0	0	0	0	563937.7

Table 7 Unit's production power for regular UC of 10 – unit 24-hour system (profit-based unit commitment)

Hr	D(MW)	Unit Number										Cost	transition. Cost
		1	2	3	4	5	6	7	8	9	10		
1	700	455	245	0	0	0	0	0	0	0	0	13683.13	0
2	750	455	295	0	0	0	0	0	0	0	0	14554.5	0
3	850	455	370	0	0	25	0	0	0	0	0	16809.45	900
4	950	455	455	0	0	40	0	0	0	0	0	18597.67	0
5	1000	455	390	0	130	25	0	0	0	0	0	20020.01	560
6	1100	455	360	130	130	25	0	0	0	0	0	22387.05	1100
7	1150	455	410	130	130	25	0	0	0	0	0	23261.98	0
8	1200	455	455	130	130	30	0	0	0	0	0	24150.34	0
9	1300	455	455	130	130	85	20	25	0	0	0	27251.06	860
10	1400	455	455	130	130	162	33	25	10	0	0	30057.55	60
11	1450	455	455	130	130	162	73	25	10	10	0	31916.06	60
12	1500	455	455	130	130	162	80	25	43	10	10	33890.16	60
13	1400	455	455	130	130	162	33	25	10	0	0	30057.55	0
14	1300	455	455	130	130	85	20	25	0	0	0	27251.06	0
15	1200	455	455	130	130	30	0	0	0	0	0	24150.34	0
16	1050	455	310	130	130	25	0	0	0	0	0	21513.66	0
17	1000	455	260	130	130	25	0	0	0	0	0	20641.82	0
18	1100	455	360	130	130	25	0	0	0	0	0	22387.04	0
19	1200	455	455	130	130	30	0	0	0	0	0	24150.34	0
20	1400	455	455	130	130	162	33	25	10	0	0	30057.55	490
21	1300	455	455	130	130	85	20	25	0	0	0	27251.06	0
22	1100	455	455	0	0	145	20	25	0	0	0	22735.52	0
23	900	455	455	0	0	0	20	0	0	0	0	17645.36	0
24	800	455	345	0	0	0	0	0	0	0	0	15427.42	0

Table 8: Power and reserve generation for 10-unit test system

Power (MW) / Reserve (MW)							
Hr	1	2	3	4	5	6	7-10
1	455/0	245/70	0/0	0/0	0/0	0/0	0/0
2	455/0	295/75	0/0	0/0	0/0	0/0	0/0
3	455/0	395/60	0/0	0/0	0/0	0/0	0/0
4	455/0	455/0	0/0	0/0	0/0	0/0	0/0
5	455/0	455/0	0/0	0/0	0/0	0/0	0/0
6	455/0	455/0	0/0	130/0	0/0	0/0	0/0
7	455/0	455/0	0/0	130/0	0/0	0/0	0/0
8	455/0	455/0	0/0	130/0	0/0	0/0	0/0
9	455/0	455/0	130/0	130/0	0/0	0/0	0/0
10	455/0	455/0	130/0	130/0	162/0	68/0	0/0
11	455/0	455/0	130/0	130/0	162/0	80/0	0/0
12	455/0	455/0	130/0	130/0	162/0	80/0	0/0
13	455/0	455/0	130/0	130/0	162/0	0/0	0/0
14	455/0	455/0	130/0	130/0	130/32	0/0	0/0
15	455/0	455/0	0/0	130/0	160/2	0/0	0/0
16	455/0	455/0	0/0	130/0	0/0	0/0	0/0
17	455/0	455/0	0/0	130/0	0/0	0/0	0/0
18	455/0	455/0	0/0	130/0	0/0	0/0	0/0
19	455/0	455/0	0/0	130/0	0/0	0/0	0/0
20	455/0	455/0	0/0	130/0	0/0	0/0	0/0
21	455/0	455/0	0/0	130/0	0/0	0/0	0/0
22	455/0	455/0	0/0	130/0	0/0	0/0	0/0
23	455/0	455/10	0/0	0/0	0/0	0/0	0/0
24	455/0	345/80	0/0	0/0	0/0	0/0	0/0

Total profit: 109661 $.

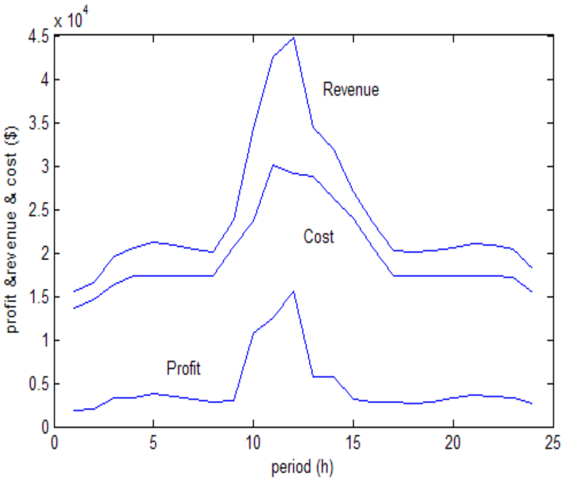

Fig.9 Revenue, generation cost and profit of GENCO for 10-unit system

Table 9 comparison between different approaches for regular UC (10-units system)

	SCUC	
Method	Cost ($)	CPU (sec)
Proposed approach	563937.7	31
LR	564892	120
GA	565825	221
EP	564551	100

Table 10 comparison between different approaches for PBUC (10-units system)

	PBUC		
Method	Cost ($)	Profit($)	CPU (sec)
Proposed approach	503123.1	109661	31
LR- EP	-	107838.57	-
Multi-Agent	-	109485.19	80
Traditional	563169.64	89184.18	-

Table 9 and 10 show a comparison between different approaches for the total production cost and computing time (CPU).The proposed approach is the best method in which as minimum generation costs and computational time in regular UC and maximum profit for profit based (deregulation) UC compared to the other approaches.

6. CONCLUSIONS

This paper concludes that the dynamic programming model can be applied to solve profit based unit commitment problem in the deregulated power system environment beside the traditional unit commitment problem. The performance of the proposed DP model when compared with the existing literature methods is found to be encouraging where a significant amount of profit can be achieved for the GENCOs. This method is simple, robust and is suitable for GENCOs in a power market. The results signify that DP is very much suitable for larger power system with more number of generating units.

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