Unit Commitment with Transmission constraints in Deregulated Power market

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***Abstract*—As the power industry across the world is undergoing a radical change by separation of transmission from generation activities, scope of competition by bidding or through provision of bilateral transactions in spot markets exists between different market players of generation and transmission. So there is a need for the unit commitment in power industry with generation biddings, load biddings and bilateral transaction biddings. In general unit commitment can be formulated as non-linear, large scale, mixed integer combinatorial optimization problem. For quick response, piece-wise linearization of cost function, slack terms with high penalty factor are incorporated in unit commitment along with all generator, system, operator and line constraints. Then unit commitment with three-part generator bidding, load bidding and bilateral transaction with both elastic and inelastic parts is performed which is suitable for the recent deregulated power industry and tested on a test case of ten generators with three bus network.**

Keywords—Deregulated power market; optimal power flow; three-part bidding; unit commitmentt;

I. INTRODUCTION

The power industry across the world is being unbundled and opened up for competition with private players unlike in vertically integrated utilities where power sector was characterized by operation of a single utility generating, transmitting and distributing electric energy in its area of operation. Separation of transmission from generation activities is one of first tasks in restructuring process of power industry. The next step is creation of competition by bidding or through provision of bilateral transactions in spot markets.

Unit commitment (UC) is the problem of determining the schedule of generating units with in a power system, subject to device and operating constraints results in great saving of electricity utilities.

Several optimizations techniques have been applied to the solution of unit commitment. Exhaustive enumerating all possible combinations in [1], priority list arranges at the generating units in start-up heuristic ordering by operating cost combined with transition costs in [2], dynamic programming searches the solution space that consists of the units status for an optimal solution in [3], integer and mixed integer programming solves the UC problem by reducing the solution search space systematically through discarding the infeasible subsets in [4], branch and bound essentially determines a lower bound to the optimal solution and then finds near optimal feasible commitment schedule in [5], lagrangian relaxation decomposes the UC problem into a master problem and more manageable sub problems that are solved iteratively in [6] have been presented and are applied to the unit commitment.

In [7], [8], [9] generic UC problem formulation and objective function as minimization of fuel costs by proper commitment of the available generating units. The total cost includes the total unit production cost, start-up cost and shut down cost. It also proposed that production cost can be modelled as polynomial curve, a piece wise constant curve or piece wise linear curve.

Different formulations of unit commitment like PBUC, SCUC, and unit commitment of power system with renewable energy sources along with respective constraints have been modelled and solved in [10].

In restructured power system, markets were divided based on their approach to supply-side bidding. Some systems used one-part incremental energy bids that take care of all accounts, while some employed three-part bids.

In [12], multi block price bids are incorporated and solved the unit commitment. Optimal power flow with transmission and security and voltage constraints are incorporated in [13], [14], [15] and penalty factor is added to limits of constraints in [15]. A set of heuristic rules is applied with OPF for unit commitment with network constraints in [16].

The process of solving unit commitment problem is a tedious process and the solution becomes more monotonous if network constraints are added to it. Here, unit commitment with network constraints is modelled and tested on a system with 10 generators and 3 buses network. In order to get fast feasible solution, piece wise linearization of cost function and slack terms are incorporated in unit commitment and tested on same test system. Based up on the literature in [17], elastic and inelastic biddings of generation and load with three part generator biddings are incorporated in unit commitment and successfully optimized with more social welfare. The model has been programmed in MATLAB-GAMS interface using DICOPT solver to solve mixed integer non-linear programming problem and GUROBI solver to solve mixed integer programming problem.

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The rest of paper organised is organized as follows. Section II formulates the unit commitment problem with network constraints. Section IV describes solution methodology. Section V provides results, comparison of the results and conclusions are stated in Section V.

II. PROBLEM FORMULATION

A. Nomenclature

n	Index of bus bar.
h	Index of period of hour.
k	Index of generator.
ld	Index of load.
ln	Index of line.
se	Index of sections of cost function.
t	Index of bilateral transaction.
z	Objective function.
pmin	Minimum generation limit.
pmax	Maximum generation limit.
Rdn	Ramp down limit.
Rup	Ramp up limit.
Rsup	Start-up ramp limit.
Rshdn	Shutdown ramp limit.
Tup	Minimum up time limit.
Tdn	Minimum down time limit.
a0	Generator cost function coefficient.
a1	Generator cost function coefficient.
a2	Generator cost function constant term.
slope	Slope of section in cost function.
pload	Load.
blmtt	Line limit.
d	Angle of bus.
p	Output power generation.
p1	Output power in section.
u	Unit status.
ustrt	Unit just start status.
usht	Unit just down status.
bidprice_gen	Bid price of generator.
pmax_bid	Elastic output generation limit.
pmax_load	Elastic load limit.
pmax_biltra	Elastic transaction limit.
pload_fix	Inelastic load.
pload_var_price	Elastic load price.
pbiltra_fix	Inelastic bilateral transaction.
pbiltra_var_price	Inelastic bilateral transaction price.
pminloadprice	Minimum load price of generator.
pbidprice	Bid price of generator.
startupprice	Start-up cost.
pload_var	Elastic load.
pbiltra_var	Elastic transaction.
χ	Reactance.
$\boldsymbol{\delta}$	Angle at bus.

B. Unit commitment

The general objective of unit commitment is to minimize system total operating cost while satisfying all of the constraints. In general it can be formulated as non-linear, large scale, mixed integer combinatorial optimization problem with both binary and continuous variables. N units for total period of H intervals, the maximum number of possible combinations is $(2^N - 1)^H$. For 24-hour period with 5, 10 units, it becomes $6.2*10^{35}, 1.73*10^{72}$ respectively.

The cost function of generator is typically expressed as a quadratic function of generator as

$$C\ (p)\ =\ a\ +\ b*p\ +\ c*p^2\ \text{ Rs} \qquad (1)$$

where C (p) is cost of production in Rupees (Rs)

P is amount of generation in MW

a, b, c are generator constants in Rs/hr, Rs/MWh, Rs/MW^2hr respectively.

Start-up cost when cooling = $C_c(1-\varepsilon^{-t/\alpha})*F+C_f$ (2)

where C_c = cold –start cost (MBtu)

F= fuel cost

C_f = fixed cost

α= thermal time constraint for the unit

t= time (h) the unit was cooled.

Start –up cost When banking= $C_t*t*F*C_f$ (3)

Where

C_t = Cost (MBtu/hr) of maintaining unit at operating temperature.

The objective function can be stated as the minimization of:

$$\sum_{h=0}^{24+\max(Tup,Tdn)} \sum_{k=1}^{n} C\big(p(k,h)\big)*u(k,h)+$$

$$\sum_{h=0}^{24+\max(Tup,Tdn)} \sum_{k=1}^{n} \Big(startupprice(k)*\big(1-u(k,h)\big)\Big) \qquad (4)$$

The objective function will be subjected to the following constraints:

i. *Generation Constraint*

Under normal operating condition, each generator has limits of sustained generation and is called as generation limit. It is not economical to load the unit below the minimum limit and the unit should not be committed above the maximum limit.

$$u(k,h)*pmin(k,h) \leq p(k,h) \leq u(k,h)*pmax(k,h) \quad (5)$$

ii. *Load Constraint*

The generated power from all the committed units must be equal to load demand.

$$\sum_{k=0}^{n} p(k,h) = pload(ld,h) \qquad (6)$$

iii. *Ramp up Constraint*

Usually Generators incur more maintenance cost when there are rapid changes in temperature or output generation, safe ramp up and safe ramp down rates are provided by manufacturer based on physical design.

Ramp up rate is the rate at which particular generator can increase its output generation in an hour. Start-up Ramp rate is the rate at which particular generator can increase its output generation in an hour while bringing a unit on-line from off

$$\begin{aligned} &p(k,h) - p(k,h-1) \leq ustrt(k,h)*Rstrt(k) \\ &+(1-ustrt(k,h))*Rup(k) \end{aligned} \qquad (7)$$

iv. *Ramp down Constraint*

Ramp down rate is the rate at which particular generator can decrease its output generation in an hour. . Shut down Ramp down rate is the rate at which particular generator can decrease its output generation in an hour while bringing down a unit off from on-line.

$$\begin{aligned} &p(k,h-1) - p(k,h) \leq usht(k,h)*Rsht(k) \\ &+(1-usht(k,h))*Rdn(k) \end{aligned} \qquad (8)$$

v. *Up time Constraint*

Thermal units usually need a crew to operate them in order to turn on and turned off. More over thermal unit can undergo only gradual temperature changes, and this necessitates into a time period of some hours required to bring unit on-line. These restrictions formulate minimum up time and minimum down constraint. Minimum up time is the time it should run, once it turned on. In Other sense it should not be turned off immediately.

$$\sum_{\tau=h}^{(h+\max(Tup(k),Tdn(k))-1)} u(k,\tau) \leq ustrt(k,h)*Tup(k) \qquad (9)$$

vi. *Down time Constraint*

Minimum down is the time it should in decommitted mode, once it turned off.

$$\sum_{\tau=h}^{(h+\max(Tup(k),Tdn(k)))-1)} (1-u(k,\tau)) \leq usht(k,h)*Tdn(k) \quad (10)$$

vii. *Must Run Constraint*

For some purposes as supply for uses outside the plant itself or for voltage support on the transmission network etc., some units are given must-run status.

$$\sigma(k,h)*u(k,h) \leq \sigma(k,h) \qquad (11)$$

$\sigma(k,h) = 1$ if unit k is a must run for a hour

$= 0$ otherwise.

viii. *Must not run Constraint*

For some maintenance reasons and on forced outages, some units are given must-not run status.

$$\sigma(k,h)*(1-u(k,h)) \leq \sigma(k,h) \qquad (12)$$

$\sigma(k,h) = 1$ if unit k is a must not run for a hour

$= 0$ otherwise.

ix. *Generating units State Logic*

$$-u(k,h-1) \leq ustrt(k,h) - (u(k,h) - u(k,h-1)) \leq u(k,h-1) \qquad (13)$$

$$-(1-u(k,h-1)) \leq ustrt(k,h) \leq (1-u(k,h-1)) \qquad (14)$$

$$(1-u(k,h-1)) \leq usht(k,h) - (u(k,h-1) - u(k,h)) \leq 1-u(k,h-1) \qquad (15)$$

$$-(1-u(k,h-1)) \leq usht(k,h) \leq u(k,h-1) \qquad (16)$$

x. *Power Flow Equation*

$$\begin{aligned} &Pinj(n,h) = \\ &\sum_{k} A_g(n,k)*p(k,h) - \sum_{ld}(A_d(n,ld)*pload(ld,h)) \end{aligned} \qquad (17)$$

Where

$A_g(n,k) = 1$ if $P(k)$ is from node n

$= -1$ if $p(k)$ is to node n

$= 0$ if $p(k)$ is not related to node n.

$A_d(n,ld) = 1$ if $pload(ld)$ is from node n

$= -1$ if $pload(ld)$ is to node n

$= 0$ if $pload(ld)$ is not related to node n.

xi. Line Flow Limits

$$Flow = A_{line} * \chi^{(-1)} * \delta \tag{18}$$

$$Flow_{\min} \leq Flow \leq Flow_{\max} \tag{19}$$

C. Unit Commitment in Dergulated Environment

The day ahead dispatch problem can be compactly formulated as follows:

minimize {-W(p)}

where W(p) is social welfare =

$$\begin{aligned}
&\sum_{h=0}^{24+\max(Tup,Tdn)} \sum_{ld=1}^{2} pload\_var(ld,h) * pload\_var\_price(ld,h) \\
&- \sum_{h=0}^{24+\max(Tup,Tdn)} \sum_{k=1}^{n} p(k,h) * pbidprice(k) \\
&- \sum_{h=0}^{24+\max(Tup,Tdn)} \sum_{k=1}^{n} ustrt(k,h) * startupprice(k) \\
&- \sum_{h=0}^{24+\max(Tup,Tdn)} \sum_{k=1}^{n} pfixed(k,h) * pminloadprice(k) \\
&+ \sum_{h=0}^{24+\max(Tup,Tdn)} \sum_{k=1}^{n} pbiltra\_var(t,h) * pbiltra\_var\_price(t,h)
\end{aligned} \tag{20}$$

The objective function will be subjected to the following constraints:

i. *Load Constraint*

$$\begin{aligned}
&Pinj(n,h) = \\
&\sum_{k} A_g(n,k) * p(k,h) - \sum_{ld} A_d(n,ld) * pload\_fix(ld,h)) \\
&+ \sum_{ld} A_{1d}(n,ld) * pload\_var(ld,h)\ ) \\
&+ \sum_{t} A_{bil}(n,t) * (pbiltra\_fix(t,h) \\
&+ \sum_{t} A_{1bil}(n,t) * pbiltra\_var(t,\ h)
\end{aligned} \tag{21}$$

Where

$A_g(n,k) = 1$ if $p(k)$ is from node n

$= -1$ if $p(k)$ is to node n

$= 0$ if $p(k)$ is not related to node n.

$A_d(n,ld) = 1$ if $pload\_fix(ld)$ is from node n

$= -1$ if $pload\_fix(ld)$ is to node n

$= 0$ if $pload\_fix(ld)$ is not related to node n.

$A_{1d}(n,ld) = 1$ if $pload\_var(ld)$ is from node n

$= -1$ if $pload\_var(ld)$ is to node n

$= 0$ if $pload\_var(ld)$ is not related to node n.

$A_{bil}(n,t) = 1$ if $pbiltra\_fix(t)$ is from node n

$= -1$ if $pbiltra\_fix(t)$ is to node n

$= 0$ if $pbiltra\_fix(t)$ is not related to node n.

$A_{1bil}(n,t) = 1$ if $pbiltra\_var(t)$ is from node n

$= -1$ if $pbiltra\_var(t)$ is to node n

$= 0$ if $pbiltra\_var(t)$ is not related to node n.

ii. *Elastic Limits*

$$P\ (k,h) < pmax\_bid(k) \tag{22}$$

$$Pload\_var\ (ld,h) < pmax\_load(ld) \tag{23}$$

$$pbiltra\_var(t,h) < pmax\_biltra(t) \tag{24}$$

III. SOLUTION METHODOLOGY

Traditional unit commitment with the objective of minimizing production cost is solved with generator limits, ramp up limits , up time and down time limits, must run, must not run constraints and network constraints using DICOPT solver.For quick solution, piece wise linearized of cost function is applied and tested on a test case. Then for convergence and feasibility, penalty factor with slack terms are incorporated as follows.

A. Piece Wise Linearization Of Cost Function

$$C(p(k,h)) = C(pmin(k)) + \sum_{s=1}^{5} slope(se,k) * p1(k,h,se) \tag{25}$$

$$P(k,h) = pmin(k) + \sum_{s=1}^{5} p1(k,h,se) \tag{26}$$

$$0 \leq p1(k,h,se) \leq \left(p\min(k) - p\max(k)\right)/5 \tag{27}$$

Where

$slope(k,s)$ is slope of section s of k th generator

$p1(k,h,se)$ is power output of k th generating unit at hour h in section s

B. Dealing Infeasibility With Penalty Factor

$$F(x) + M1 * Z1 + M2 * Z2 \tag{28}$$

$$f(x) \leq c1 + Z1 \tag{29}$$

$$g(x) \leq c2 + Z2 \tag{30}$$

where *M1, M2* are penalty factors

F(x) is objective function

f(x), g(x) are inequality constraints

Z1, Z2 are slack terms

C. *UC in Deregulated Environment*

Unit commitment in restructured power systems in tune with traditional unit commitment is performed, with the objective of maximizing social welfare. Start-up cost and fixed cost are paid only if the generator is not turned on by itself. It is explained as follows , if generator with minimum uptime of three hours is turned on fourth hour by generator itself, then up to minimum up time hours for that generator, there should be no start-up cost and fixed cost are paid to the generator even if generator is turned on by unit commitment.

In addition to provision of whether to pay start up and fixed cost, three part generator biddings, load bidding and bilateral transaction bidding is included to the unit commitment for maximum social welfare and tested on a test system of 10 generators with three bus network .

IV. TEST SYSTEMS AND RESULTS

Unit Commitment with specifications shown in table I, load requirement in Table II, network limits in table III with unit initial status in Table IV is solved on a 10 generator, 3 bus network. Result of UC problem with objective of minimum cost of generator is in table V and respective time requiremt in Table VI.

A. *Unit Commitment*

TABLE 1 FEATURES OF THE 10 UNIT SYSTEM

Unit no	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
a($/h)	0.00048	0.00173	0.00031	0.00222	0.002
b($/MWh)	16.19	27.79	17.26	27.27	16.6
c($/ MW^2h)	1000	670	970	665	700
Max MW	455	55	455	55	130
Min MW	150	10	150	10	20
Rampdn(MW)	142	52	142	147	185
Rampup(MW)	300	211	186	198	212
Sdrmp(MW)	455	55	455	55	130
Strmp(MW)	455	55	455	55	130
Mindwt(h)	0	1	0	1	0
Minup(h)	5	3	2	1	4
Pminload price($)	3439.3	948.073	3565.975	937.922	1032.8
Startup price($)	20	30	50	12	0

TABLE 1 (CONTINUED)

Unit no	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
a($/h)	0.00712	0.00211	0.00079	0.00398	0.00413
b($/MWh)	22.26	16.5	27.74	19.7	25.92
c($// MW^2h)	370	680	480	450	660
Max MW	80	130	85	162	55
Min MW	20	20	25	25	10
Rampup(MW)	148	163	186	178	176
Rampdown(MW)	193	245	235	289	321
Strmp(MW)	80	130	85	162	55
Sdrmp(MW)	80	130	85	162	55
Mindwt(h)	4	1	5	0	0
Minupt(h)	2	3	1	4	2
Pminload price($)	818.048	1010.844	1173.994	944.9875	919.613
Startupprice($)	12	86	10	45	20

TABLE II LOAD PROFILE CORRESPONDING TO THE 10 UNIT SYSTEM

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

TABLE III FLOW LIMITS

Line no	Susceptance(pu)	Power Rating Of lines(pu)
1	2.5	2.5
2	3.5	3.5
3	1.4	1.4

TABLE IV INITIAL UNIT STATUS

Unit no	Generator Initial Status(ON/OFF)	Initial Generated Amount(MW)
unit1	1	200
unit2	0	0
unit3	0	0
unit4	0	0
unit5	0	0
unit6	0	0
unit7	1	50
unit8	0	0
unit9	0	0
unit10	0	0

TABLE V RESULT (ECONOMIC STATUS)

System	Unit Commitment
10 unit	22028941.6408$

TABLE VI RESULT (AVERAGE TIME REQUIREMNT)

System	Average time(sec)
10 unit	54.412

B. *Unit Commitment with piece wise linearization*

Unit commitment specifications listed Tables I, II, III, IV with piece wise linearization of cost function is solved and result is in Tables VII and VIII

TABLE VII RESULT (ECONOMIC STATUS)

System	Unit Commitment
10 unit	3795244706.3460$

TABLE VIII RESULT (AVERAGE TIME REQUIREMNT)

System	Average time(sec)
10 unit	0.659

C. *Unit Commitment in Deregulated Market*

Unit commitment with three part biddings of generators i.e. fixed cost , minimum load cost and generated cost with elastic and inelastic load and generation with specifications in Tables IX,X along with specification in Tables I,II,III,IV is solved and result are shown in Tables XI,XII.

TABLE IX FIXED BILATERAL TRANSACTION SPECIFICATION

Hour no	trans(MW|)	Hour No	Trans(MW)	Hour	Trans(MW)
1	120	9	0	17	120
2	0	10	90	18	0
3	45	11	0	19	0
4	0	12	0	20	0
5	60	13	140	21	120
6	0	14	0	22	0
7	80	15	250	23	0
8	50	16	0	24	

TABLE X FIXED LOAD SPECIFICATION

Hour	Load(MW)	Hour	Load(MW)	Hour	Load(MW)
1	200	9	40	17	100
2	100	10	100	18	50
3	200	11	150	19	80
4	100	12	140	20	70
5	50	13	130	21	100
6	100	14	200	22	50
7	150	15	45	23	100
8	100	16	80	24	150

TABLE XI RESULT (ECONOMIC STATUS)

System	Unit Commitment
10 unit	-2215264.00$

TABLE XII RESULT (AVERAGE TIME REQUIREMNT)

System	Average time(sec)
10 unit	0.047

V. CONCLUSION

Unit commitment with network constraints is solved on a quadratic cost curve of generators. Subsequently it is solved on a piece wise linearized cost curve of generator. Piecewise linearization gives quicker solution but incurred more cost. Unit commitment with three-part generator bidding, elastic and inelastic load bidding, elastic and inelastic bilateral transaction with reasonable startup and fixed cost is solved. This gives a scope for improving social benefit and solving unit commitment comparatively faster.

TABLE XIII COMPARATIVE RESULTS (ECONOMIC STATUS)

System	Economic status ($)
Unit Commitment with network constraints	22028941.64
UC with network constraints with piecewise linearization	3795244706.34
UC in deregulated market	-2215264.00

TABLE XIV COMPARATIVE RESULT (AVERAGE TIME REQUIREMNT)

System	Average time(sec)
Unit Commitment with network constraints	54.412
UC with network constraints with piecewise linearization	0.659
UC in Deregulated market	0.047

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