Stochastic Unit Commitment using Two Point Estimate Method with Proliferation of Wind Power

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***Abstract*—The inherent flexibility of the power system is becoming weak with the proliferation of wind generators into the traditional power system. The intermittent and uncertain wind power adds to the problem of balancing load and generation. The proposal is made in two steps: in first step, a stochastic unit commitment model is presented for scheduling of the generating units while taking note of uncertainties in terms of load and wind generation by using two point estimate method. In the second step, an analytical study is presented such that the participation of different generating units for providing generation and flexibility. With this, a comparison between the proposed approach and the deterministic approach is also presented. The proposed approach is validated on modified IEEE RTS-96 system (including 96 conventional generating units and 19 wind farms).**

I. Introduction

The never lasting increase in electricity demand and the technical modernization of supply has increased stress on the power system. Today, the power sector world is adopting clean, cheap and sustainable sources of power and there is no doubt that the renewable sources have emerged as great options. Wind energy source is quite popular for its sustainability and cleanliness at very low cost and is being integrated with power system. The load keeps changing with time and can be even estimated, but it shows significant fluctuation in real time. Hence, unit commitment is done for secured and reliable power delivery.

Unit commitment (UC) is an optimization problem used to determine the operation schedule of the generating units at every hour interval with varying loads under different constraints and environments. In other words, it can be stated as a problem of finding the order and schedule in which the units are to be started up and shut down over a period of time, say 24 hour, so the total operating cost is minimum subjected to the specified constraints. UC schedules the hourly on/off status and the MW outputs of each generating unit. The complexity of the UC problem proportionally increases with the number of units and considered constraints. For a large generating system, UC problem becomes a nonlinear, large scaled, mixed integer problem usually with large number of continuous and binary variables. Many different ways have been used to model a unit commitment problem depending on the selection of the constraints and optimization methods. In many research work, UC problem is modeled with classical optimization method like linear programming [1], lagrangian relaxation [2], dynamic programming [3], [4], mixed integer programming [5], branch and bound method [6], interior point method [7], benders decomposition [8]. Metaheuristic optimization methods like genetic algorithm [9], tabu search method [11], [12], neural network [11], particle swarm optimization technique [10], fuzzy algorithms [13] and binary fish swarm algorithm [14] have been used for modeling the complicated UC problem in many research work.

With integration of wind energy generators to the traditional power system, change in generating unit schedule and output is seen. The generation from costlier conventional generating unit reduces with increase in the level of wind penetration. Hence, the inherent flexibility of the power system gets weakened with integration of wind energy sources. Moreover, the random nature of wind results to intermittent power generation from the wind farm which consequently increases randomness in net demand. It raises problem in balancing the load and generation. The probabilistic methods such as monte carlo simulation method, Fast fourier transformation,point estimate method can be used for assessing the uncertainty in the net load of the power system. Monte Carlo Simulation (MCS) is the most commonly used simulation method due to its high accuracy [4]. Its execution can be extremely time-consuming. In this paper, two point estimate method (2PEM) is used to get rid of the time-consuming MCS method. The 2PEM requires a small level of data such as some of the statistical moments (i.e., mean, variance, skewness, and kurtosis) for approximating the probability functions of the uncertain variables [15].

Section II of this paper describes the two point estimate method which is used to provide generation schedule for real time considering uncertainties of wind generation and load. The problem formulation for both deterministic and stochastic UC models are discussed in Section III of the paper. Section IV demonstrates results and discussion and Section V presents the concluding remarks.

II. Two Point Estimate Method

Two point estimate method is basically a variation of the original point estimate method (PEM). The problem is decomposed into several subproblems. The deterministic OPF is then run twice for each uncertain variable, once for the value

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below mean, and once for the value above the mean, with other variables kept at their means. The steps are as follows:

1) Determine the number of uncertain variables (κ)
2) Set $\xi(y) = 0$ and $\xi(y^2) = 0$
3) Set variable, $v = 1$
4) Calculate the locations of concentrations, $\eta_{v,1}$ and $\eta_{v,2}$

$$\eta_{v,1} = \sqrt{\kappa} \tag{1}$$

$$\eta_{v,2} = -\sqrt{\kappa} \tag{2}$$

5) Calculate the probability of both concentrations, $\mathrm{P}_{v,1}$ and $\mathrm{P}_{v,2}$

$$\mathrm{P}_{v,1} = \mathrm{P}_{v,2} = \frac{1}{2\kappa} \tag{3}$$

6) Finding out the two concentrations, $x_{v,1}$ and $x_{v,2}$

$$x_{v,1} = \mu_{X,v} + \eta_{v,1}\sigma_{X,v} \tag{4}$$

$$x_{v,2} = \mu_{X,v} + \eta_{v,2}\sigma_{X,v} \tag{5}$$

where $\mu_{X,v}$ and $\sigma_{X,v}$ are the mean and the standard deviation of X_v , respectively.

7) Run OPF for both concentrations, $x_{v,1}$ and $x_{v,2}$ using $X = [\mu_{X,1}, \mu_{X,2}, ..., \mu_{v,1}, ...\mu_{X,\kappa}]$ and $X = [\mu_{X,1}, \mu_{X,2}, ..., \mu_{v,2}, ...\mu_{X,\kappa}]$ respectively.
8) Update the $\xi(y)$ and $\xi(y^2)$

$$\xi(y) = \Sigma_v \Sigma_i \left(P_{v,i}\left(h\left[\mu_{X,1}, \mu_{v,i}, \mu_{X,\kappa}\right]\right)\right) \tag{6}$$

$$\xi(y^2) = \Sigma_v \Sigma_i \left(P_{v,i}(h\left[\mu_{X,1}, \mu_{v,i}, \mu_{X,\kappa}\right])^2\right) \tag{7}$$

where $v = 1, 2, ..\kappa$ and i= 1,2

9) Evaluate the mean and standard deviation

$$\mu_y = \xi(y) \tag{8}$$

$$\sigma_y = \sqrt{\xi(y^2) - \mu_y^2} \tag{9}$$

10) Repeat steps 4 to 9 for all uncertain variables

III. Problem Formulation

UC plays vital role in secured and reliable operation of the power system. It schedules on/off pattern and generation output of all generating units to meet the load at minimum operating cost for a given time interval. The problem formulation is done for lossless dc models for deterministic and stochastic UC problems.

A. Deterministic unit commitment with wind penetration

The objective of deterministic unit commitment is to minimize the total generation cost subjected to power balance, generating unit minimum and maximum outputs, ramp limits, minimum up and down times and transmission line constraints. With the assumption that system operator owns the wind generators, no cost is associated with the wind farms and it act as negative loading.

a) Objective function: The objective is minimization of generating cost i.e. sum of fixed, production and start-up cost as explained in (10)

$$Min \sum_{t=1}^{T}\sum_{i=1}^{I}\left(A_i.u_i(t) + \sum_{s=1}^{S} k_s.G_{i,s}(t) + SU_i^{cost}(t)\right) \tag{10}$$

where *t* denotes hours (1 to T), *i* denotes generating units (1 to I), A_i is fixed production cost for generating unit *i*, $u_i(t)$ is binary variable which is equal to 1 if generating unit *i* produces at time *t* otherwise equals to 0, *s* denotes cost curve segments for generating units (1 to S), k_s denotes slope for the cost curve segment *s* of generating unit *i*, $G_{i,s}(t)$ denotes output of generating unit *i* on segment *s* at time *t*, $SU_i^{cost}(t)$ is start-up cost of generating unit *i* at time *t*.

b) Constraints: Constraints reveal the limitations of the generating units for secure and reliable operation of power system.

- Power balance constraints

$$\sum_{i=1}^{I} G_i(t) + \sum_{w=1}^{W} WG_w(t) - \sum_{\{m,n\}\in l|n>m} \frac{\delta_m(t) - \delta_n(t)}{X_{mn}} + \sum_{\{m,n\}\in l|n<m} \frac{\delta_n(t) - \delta_m(t)}{X_{mn}} = d_m(t) \;\; \forall \mathrm{t} \le \mathrm{T}, \mathrm{m} \le \mathrm{B} \tag{11}$$

where $G_i(t)$ is output of generating unit *i* at time *t*

$$G_i(t) = \sum_{s=1}^{S} G_{i,s}(t) \tag{12}$$

and $WG_w(t)$ is wind generation by wind generating unit *w* at time *t*, *w* is index for wind generating unit, 1 to W, *b* indicates buses(1 to B), *l* shows lines(1 to L), $\delta_m(t)$ and $\delta_n(t)$ denote voltage angle at bus *m* and bus *n* in radian at time *t*, respectively, X_{mn} shows reactance of line connecting nodes *m-n* and $d_m(t)$ is demand at bus *m*.

- Generation limit constraints

$$G_i^{min}(t) \le G_i(t) \le G_i^{max}(t) \tag{13}$$

where $G_i^{min}(t)$ and $G_i^{max}(t)$ are minimum and maximum output of generating unit *i* at time *t*, respectively.

- Ramp limits constraints
  Maximum ramp up rate

$$ramp_i^{up} \ge G_i(t+1) - G_i(t) \tag{14}$$

Maximum ramp down rate

$$-ramp_i^{down} \le G_i(t+1) - G_i(t) \tag{15}$$

where $G_i(t+1)$ and $G_i(t)$ indicate output of generating unit *i* at time hour *t+1* and *t*, respectively.

- Minimum up and down times constraints

$$u_i(t) = G_i^{on\_off}(t) \;\; \forall i \le I, t \le Td_i^{up,min} + Td_i^{down,min} \tag{16}$$

where
$G_i^{on\_off}(t)$ is on-off status of generating unit *i* at time *t*, $Td_i^{up,min}$ is duration of time for which generating unit *i* has to be on at the beginning of the planning horizon, $Td_i^{down,min}$ is duration of time for which generating unit *i* has to be off at the beginning of the planning horizon.

$$\sum_{tt=t-G_i^{up}+1}^{t} u_i^{su}(tt) \leq u_i(t) \;\; \forall\, t \geq Td_i^{up,min} \tag{17}$$

$$\sum_{tt=t-G_i^{down}+1}^{t} u_i^{sd}(tt) \leq 1 - u_i(t) \;\; \forall\, t \geq Td_i^{down,min} \tag{18}$$

where
$u_i^{su}(tt)$ and $u_i^{sd}(tt)$ are start-up and shutdown binary variables for generating unit *i* at time *t*, respectively.

$$Td_i^{up,min} = max\{0, min\{T, (G_i^{up} - G_i^{up,int}).G_i^{on\_off}\}\} \tag{19}$$

$$Td_i^{down,min} = max\{0, min\{T, (G_i^{down} - G_i^{down,int}) (1 - G_i^{on\_off})\}\} \tag{20}$$

where
G_i^{up} and G_i^{down} are minimum up and down time of generating unit *i*, respectively, $G_i^{up,int}$ and $G_i^{down,int}$ are the time for which generating unit *i* has been up and down already before *t = 0*, respectively, $G_i^{on\_off}$ is on-off status of generating unit *i* at *t = 0*.

- Line flow constraints

$$l_{mn}^{min} \leq \frac{\delta_m(t) - \delta_n(t)}{X_{mn}} \leq l_{mn}^{max} \tag{21}$$

where l_{mn}^{min} and l_{mn}^{max} is minimum and maximum capacity of line between node *m* and *n*.

- Voltage angle constraints

$$-\pi \leq \delta_b(t) \leq \pi \qquad \forall\, t \leq T, \forall\, b \leq B \tag{22}$$

voltage angle for all bus except the reference bus.
For reference bus, the voltage angle is

$$\delta_b(t) = 0 \qquad \forall\, t \leq T \tag{23}$$

Wind energy penetration means the percentage of total annual demand supplied by wind energy. Assumed if the total wind energy generation is 300MWh for 24 hour and total demand for 24 hour is 900 MWh then wind energy penetration is 300/900 i.e 33.33%. It evaluates the wind contribution in total electrical energy consumption. However, the maximum allowable wind energy penetration is limited by the flexibility of the conventional generating unit.

Generating units ramp up and down, startup or shutdown to meet the net load at different time hour in different manner. This can be termed as generation cycle. The generation cycle is the percentage of difference between the generation output of a generating unit in two successive time hour to the maximum capacity of that generating unit and can be explained as (24). It shows the ramping behavior of generating units with respect to change in load.

$$Gencyc_i(t) = \frac{G_i(t) - G_i(t-1)}{G_i^{max}} * 100 \tag{24}$$

B. Stochastic unit commitment with wind penetration

The stochatsic unit commitment determines the operation schedule of the generating units at every hour interval with varying loads under different constraints and environments considering the uncertainties in the input parameters. Here, the loads and wind generation are taken as uncertain variables and two point estimate method (2PEM) is used for solving the stochastic problems. κ is number of uncertain variable,2κ are the number of scenarios which will get generated and deterministic unit commitment is run for all the scenarios. Different scenarios are generated by (1)-(5). The problem is formulated with objective function as (10) subjected to power balance constraint as (25) and other constraints as (12) - (23) for each scenarios and generation output is updated with (6)-(9).

$$\sum_{i=1}^{I} G_i(t) + \sum_{w=1}^{W} WG_w^{new}(t) - \sum_{\{m,n\}\in l|n>m} \frac{\delta_m(t) - \delta_n(t)}{X_{mn}} + \sum_{\{m,n\}\in l|n<m} \frac{\delta_n(t) - \delta_m(t)}{X_{mn}} = d_m^{new}(t) \;\; \forall\, \mathrm{t} \leq \mathrm{T}, \mathrm{m} \leq \mathrm{B} \tag{25}$$

where $WG_w^{new}(t)$ is new uncertain wind generation by wind generating unit *w* at time *t* considering deviation in wind, $d_m^{new}(t)$ is new uncertain demand by bus *m* at time *t* considering deviation in load.

IV. Result and Discussion

A. Input Data

Unit commitment models are made in General algebraic modeling system (GAMS) 23.5.2 environment. GAMS solver CPLEX has been used to solve the mixed integer linear programming UC problem. These models are applied to modified IEEE RTS 96 system for 24 hour with hourly resolution. The cost functions, initial conditions and detailed data regarding the limits for generation, ramp and start up and shut down of the generating unit are taken from [16]. The data for system bus, load, transmission line and generating units at each bus is used from [17]. System load for performing UC is taken for Monday of the first week of the winter season considering 10% increase in the annual load. Hourly load is taken in percentage of daily peak load as per a weekday of the winter season. The total demand of the system for 24 hour is 150189.077 MWh. TABLE I shows position, capacity and generation of wind energy generating units for 24 hour time horizon.

B. Case Studies

Case 1. Deterministic unit commitment with wind penetration

The main aim of the deterministic UC is to schedule generating unit to satisfy the load at minimum generation

TABLE I
WIND DATA

Wind units	w1	w2	w3	w4	w5	w6	w7	w8	w9	w10	w11	w12	w13	w14	w15	w16	w17	w18	w19
Bus	102	114	116	117	118	119	120	121	123	202	202	212	213	219	220	223	301	306	309
Capacity	300	300	600	600	300	600	600	300	300	150	300	300	300	150	600	600	150	300	150
Wind generation for 24 hours																			
Time	**w1**	**w2**	**w3**	**w4**	**w5**	**w6**	**w7**	**w8**	**w9**	**w10**	**w11**	**w12**	**w13**	**w14**	**w15**	**w16**	**w17**	**w18**	**w19**
t1	25.914	63.304	91.816	92.715	8.092	291.444	359.794	0.954	192.759	11.708	14.560	65.726	49.001	109.435	267.422	214.608	18.039	17.501	38.144
t2	13.109	41.798	83.912	78.715	23.066	258.661	350.863	7.808	178.390	9.423	14.064	56.429	70.378	100.714	319.525	168.113	19.004	22.973	32.540
t3	26.710	45.556	92.964	107.476	28.795	222.181	255.078	30.262	134.787	6.339	12.896	52.615	46.451	32.725	261.952	130.416	11.083	43.057	22.015
t4	91.398	89.740	164.088	149.987	19.216	105.933	232.755	31.686	98.439	13.785	38.933	47.460	42.147	6.732	186.965	68.906	9.740	82.751	14.070
t5	118.838	89.824	206.072	107.224	7.695	40.065	254.307	27.059	81.550	31.425	52.809	65.472	43.151	6.177	160.651	57.835	27.972	130.912	16.809
t6	99.119	100.056	177.367	58.673	5.383	105.302	376.145	29.066	96.038	20.792	33.289	92.437	86.921	18.767	195.611	121.965	55.259	139.387	32.288
t7	106.492	167.805	162.136	64.697	5.263	142.796	270.845	19.874	195.189	24.190	23.429	139.665	118.783	40.291	264.738	212.507	33.695	113.402	35.832
t8	212.326	149.189	145.068	42.044	8.883	175.319	375.095	6.920	200.904	57.579	80.091	195.592	193.051	74.171	295.824	289.256	16.350	94.112	36.837
t9	279.244	103.814	165.715	25.593	6.523	228.110	403.312	4.020	137.666	131.299	215.390	190.354	157.696	92.374	453.426	367.424	6.952	106.246	49.170
t10	279.995	83.124	214.478	58.664	10.855	256.853	366.882	4.216	185.024	141.331	274.408	249.078	214.375	95.430	465.075	404.316	4.593	156.187	70.938
t11	239.459	97.335	242.821	144.591	12.528	247.660	408.412	3.999	195.995	137.757	278.160	251.612	269.442	89.271	481.686	447.020	9.686	192.110	79.729
t12	261.094	63.840	165.360	87.633	13.041	103.328	418.833	4.007	154.554	136.099	282.553	266.543	275.189	77.145	513.445	493.130	108.973	251.122	79.515
t13	276.962	162.596	103.648	41.092	11.047	284.046	398.264	6.266	172.559	140.820	288.171	267.273	284.282	85.959	539.259	522.955	137.459	252.313	107.471
t14	235.495	219.563	106.706	40.213	7.318	284.879	420.095	20.090	249.293	145.802	289.441	287.635	286.696	83.508	556.941	512.663	139.992	261.385	131.435
t15	210.709	251.811	194.079	189.120	2.938	345.818	425.648	16.380	257.118	146.590	284.162	289.265	285.048	94.957	559.522	479.922	135.148	259.146	142.975
t16	256.520	253.147	365.709	361.928	2.076	505.234	505.779	8.670	274.278	145.976	277.811	288.267	289.318	92.306	532.987	496.204	84.773	234.253	144.955
t17	276.083	263.118	448.830	438.146	12.095	549.595	544.398	17.618	289.543	141.552	245.133	288.445	287.425	79.664	540.362	519.533	121.477	231.927	146.436
t18	282.357	271.355	473.774	488.717	30.202	550.261	537.728	56.451	293.425	136.215	230.864	287.394	286.233	62.193	566.459	548.491	134.338	217.808	146.774
t19	255.403	252.950	491.931	445.412	39.506	543.738	528.473	76.319	292.268	131.302	226.958	287.960	287.900	87.158	577.537	563.488	128.593	121.985	146.134
t20	177.938	247.701	381.516	339.317	76.274	525.438	510.175	63.190	283.526	139.897	247.145	286.854	287.215	129.459	572.871	551.850	128.486	152.865	146.546
t21	103.050	216.973	412.159	407.070	103.671	494.778	417.873	98.482	263.790	126.694	226.471	261.945	290.468	127.864	528.652	542.363	134.325	273.477	145.320
t22	133.305	151.739	395.758	360.760	112.276	490.185	446.777	139.384	263.953	73.350	130.177	195.534	245.493	116.051	500.509	532.144	108.105	262.790	139.039
t23	229.781	136.030	244.180	227.718	80.165	382.676	398.803	99.292	250.679	71.913	96.402	209.530	207.546	98.179	488.275	455.928	85.133	277.074	125.566
t24	236.264	93.737	106.426	138.126	42.987	209.193	257.663	57.513	182.979	101.701	246.877	171.440	195.870	37.783	413.553	348.102	95.685	221.345	122.068

cost subjected to a number of constraints. The unit commitment allows the cheaper generators to generate and meet demand firstly and then the costlier one are committed. Limits for ramp, transmission and minimum up and down time of generating units may schedule costlier generating unit before cheaper generating units to meet the demand. Wind energy penetration means the percentage of total day (24 hr) load shared by the wind. The increment in wind energy penetration leads to curtailment in the net load and hence, reduces the overall production cost from conventional sources. The costlier generator are avoided for production and changes is seen for the time at which maximum load occurs. This aggravate the condition in context to flexibility requirement. Higher flexible units shows more cycling to meet the demand. Fig.1 depicts netload to be served by conventional generating units at different levels of wind penetration. Fig.2 shows different type of cost associated in generation for different scenarios.

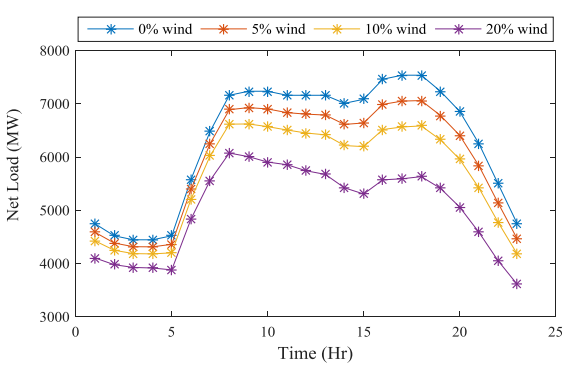


Fig. 1. Net load of the system at different level of wind penetration

Case 1a. Deterministic unit commitment without wind penetration: No wind penetration is considered in this case and the conventional generating units of the system has to

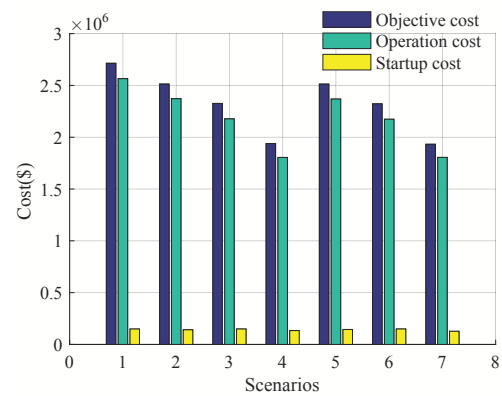


Fig. 2. Different types of cost associated in generation at different level of wind penetration (a) scenarios 1-4 without uncertainty in load and wind (b) scenarios 5-7 with uncertainty in load and wind

meet the demand (150189.077 MWh) for next 24 hour. Fig.1 depicts thats maximum load is at 18th and 19th hour at 0% wind penetration. Fig.3 shows the contribution of different type of generating units in satisfying the demand in terms of percentage of total 24 hr demand. Scenario 1 of Fig.3 presents that maximum contribution in generation is of U400, U197, U100, U155, U76 and U350 (descending order). The generating unit U12, U20 and U50 are not scheduled for generation. However U12, U20 and U50 shut down and its participation is 3.12%, 2.0833% and 4.1667% of overall cycling by the generating units in 24 hour time horizon respectively and is depicted in scenario 1 of Fig.4. U155, U76 and U100 have maximum involvement in ramping to meet the demand while the generating unit U155 and U350 ramps up to meet the maximum demand at 18th and 19th hour.

Case 1b. Deterministic unit commitment with 5% wind penetration: For this case 5% wind penetration is allowed, which means the conventional generating units of the system

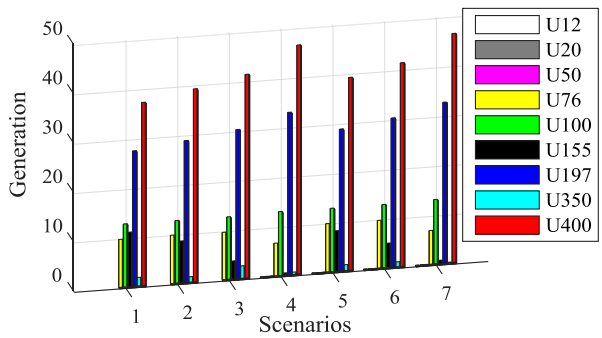


Fig. 3. Contribution of generating units in meeting net demand(24hr) for different scenarios

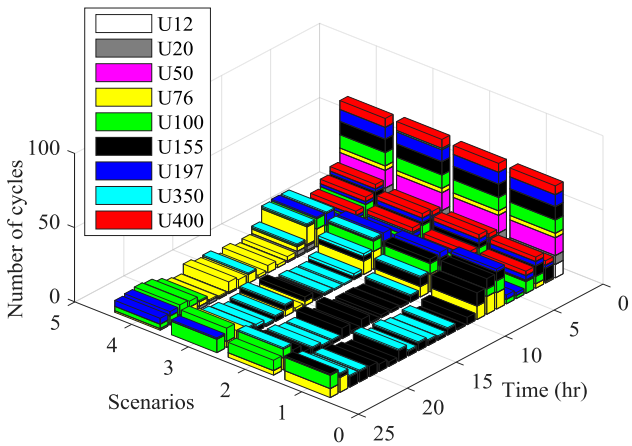


Fig. 4. Participation of different type of generating units in cycling at different level of wind penetration without considering uncertainties

has to meet 142679.623 MWh demand for next 24 hour. Fig.1 depicts thats maximum load is at 19th hour at 5% wind penetration and scenario 2 of Fig.3 shows maximum contribution in generation is of U400, U197 and U100. Generation of U76 increases while U155 decreases. The generating unit U12, U20 and U50 are not scheduled for generation. U155, U100 and U76 have maximum involvement in ramping to meet the demand as depicted in scenario 2 of Fig.4. The generating unit U155 and U350 ramps up to meet the maximum demand at 19th hour.

Case 1c. Deterministic unit commitment with 10% wind penetration: With 10% wind penetration, the net demand to be meet by conventional generating units in next 24 hour is 135170.169 MWh. Fig.1 depicts thats maximum load is at 10th hour at 10% wind penetration and scenario 3 of Fig.3 shows maximum contribution in generation is of U400, U197 and U100. Generation of U350 increases while U155 decreases. Again, in this case the units U12, U20 and U50 are not scheduled for generation. U155, U100 and U76 have maximum involvement in ramping to meet the demand shown in scenario 3 of Fig.4. The generating unit U155 and U350 ramps up to meet the maximum demand at 10th hour.

Case 1d. Deterministic unit commitment with 20% wind penetration: In this case, the net load of 120151.261 MWh is to be served by the conventional generating units and the maximum load is at 9th hour. Scenario 4 of Fig.3 shows maximum contribution in generation is of U400, U197, U100 and U76. Contribution of U155 and U350 shows decrement in generation. Scenario 4 of Fig.4 represents U100, U76, U155 and U350 have maximum involvement in ramping to meet the net demand. The generating units U20, U12 and U50 get started up to meet the maximum demand at the 9th hour.

Case 2. Stochastic unit commitment with wind penetration

For stochastic unit commitment, both wind and load are taken as variables. 2PEM is used for generating different scenarios by considering deviation of 5% in wind generation and 10% in load demand. Curtailment in the total generation cost is seen with increase in wind penetration. Even, the total generation cost of stochastic UC is lesser in comparison to deterministic UC of the system. The overall generation cost reduces with increase in wind energy penetration where startup cost increases while operational cost decreases for lower penetration level and vice versa for higher wind energy penetration level. The cycling of generating unit increases in the stochastic scenarios.

Case 2a. Stochastic unit commitment with 5% wind penetration: The generating cost is lower than deterministic UC but startup cost increases as unit U50, U20 and U12 are made ON to meet the uncertain fluctuation in net demand. The pattern of contribution in generation by these units i.e. U400, U197, U100, U76 and U155 contributes in descending order is shown as scenario 5 of Fig.3 . U155, U76 and U100 shows maximum participation in cycling and can be depicted as scenario 5 of Fig.5. Generating units shows more cycling on considering uncertainties. U20, U50, U155 and U350 ramp up to meet the maximum demand at 19th hour.

Case 2b. Stochastic unit commitment with 10% wind penetration: In this case, the generation cost reduces but startup cost increases in comparison to deterministic UC. The unit U350, U50, U20 and U12 are started up to meet significant change in net demand. U155, U100 and U76 have maximum involvement in ramping to meet the demand as shown in scenario 6 of Fig.5. Maximum contribution in generation is of U400, U197 and U100 and is depicted as Scenario 6 of Fig.3. The generating unit U12, U20, U50, U155 and U76 shows high fluctuation while U100, U350 and U400 shows little variance to meet the maximum demand at 10th hour.

Case 2c. Stochastic unit commitment with 20% wind penetration: In this case, both the cost for generation and startup decreases in comparison to deterministic UC. The unit U350, U50, U20 and U12 are started up to meet significant change in net demand. U155, U100 and U76 have maximum involvement in ramping to meet the demand shown in scenario 7 of Fig.5. Scenario 7 of Fig.3 depicts maximum contribution in generation is of U400, U197 and U100. The generating unit U12, U20, U50, U76 and U155 shows high variation to meet the maximum demand at 9th hour.

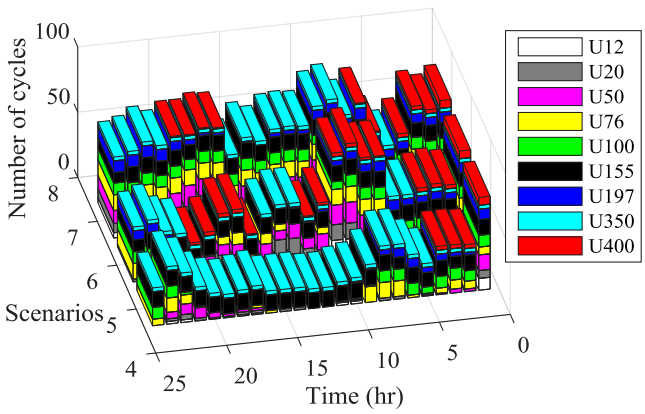
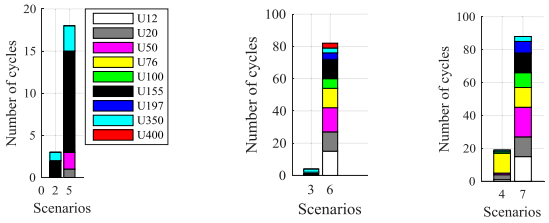


Fig. 5. Participation of different type of generating units in cycling on considering uncertainties at different level of wind penetration

Fig.6 shows the participation of different types of generating units in meeting maximum demand for deterministic and stochastic schedule with different level of wind penetration at the forecasted peak hours. Significant variation in cycling of the generating units is depicted.



(a) (b) (c)

Fig. 6. Participation of different types of generating unit in meeting maximum demand for deterministic and stochastic schedule (a) with 5% wind penetration at time hour 19 (b) with 10% wind penetration at time hour 10 (c) with 20% wind penetration at time hour 9

V. Conclusion

In this paper, a stochastic UC problem is modeled by applying 2PEM considering the uncertainties of wind and demand. The generation schedule varies dramatically on including uncertainty at different level of wind energy penetration. On analyzing the results of both deterministic and stochastic UC, it can be concluded that the contribution of generating unit U400 and U197 remains maximum while contribution of unit U155 and U350 in generation decreases in meeting the net demand with increase in wind penetration. Unit U100 and U76 participation in generation increases and the costlier generating units with high flexibility like U20, U50 and U12 are required to meet peak demand at high wind energy penetration. Generation contribution is in same pattern U400, U197, U100, U76, U155, U350, U20, U12 and U50 (in decreasing order of their contribution) but there is increase in contribution of U12, U20, U50, U76, U100 in generation on considering increment in uncertainties either in terms of deviation or wind energy penetration level. It can be concluded that the cheaper generating units have high contribution in generation while costlier generating units with high flexibility have high contribution in providing flexibility for the significant change in demand on considering uncertainties due to deviation of wind and load and increment in wind energy penetration.

References

[1] A. Grey and A. Sekar, "Unified solution of security-constrained unit commitment problem using a linear programming methodology," *IET Generation, Transmission Distribution*, vol. 2, no. 6, pp. 856–867, November 2008.

[2] T. Seki, N. Yamashita, and K. Kawamoto, "New local search methods for improving the lagrangian-relaxation-based unit commitment solution," *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 272–283, Feb 2010.

[3] Y. Fu, M. Shahidehpour, and Z. Li, "Security-constrained unit commitment with ac constraints," *IEEE Transactions on Power Systems*, vol. 20, no. 3, pp. 1538–1550, Aug 2005.

[4] J. J. Hargreaves and B. F. Hobbs, "Commitment and dispatch with uncertain wind generation by dynamic programming," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 4, pp. 724–734, Oct 2012.

[5] J. Ostrowski, M. F. Anjos, and A. Vannelli, "Tight mixed integer linear programming formulations for the unit commitment problem," *IEEE Transactions on Power Systems*, vol. 27, no. 1, pp. 39–46, Feb 2012.

[6] C. L. Chen and S. C. Wang, "Branch-and-bound scheduling for thermal generating units," *IEEE Transactions on Energy Conversion*, vol. 8, no. 2, pp. 184–189, Jun 1993.

[7] I. A. Farhat and M. E. El-Hawary, "Interior point methods application in optimum operational scheduling of electric power systems," *IET Generation, Transmission Distribution*, vol. 3, no. 11, pp. 1020–1029, Nov 2009.

[8] J. Wang, M. Shahidehpour, and Z. Li, "Security-constrained unit commitment with volatile wind power generation," *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1319–1327, Aug 2008.

[9] I. G. Damousis, A. G. Bakirtzis, and P. S. Dokopoulos, "A solution to the unit-commitment problem using integer-coded genetic algorithm," *IEEE Transactions on Power Systems*, vol. 19, no. 2, pp. 1165–1172, May 2004.

[10] A. Y. Saber, T. Senjyu, A. Yona, and T. Funabashi, "Unit commitment computation by fuzzy adaptive particle swarm optimisation," *IET Generation, Transmission Distribution*, vol. 1, no. 3, pp. 456–465, May 2007.

[11] C. C. A. Rajan, M. R. Mohan, and K. Manivannan, "Neural-based tabu search method for solving unit commitment problem," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 150, no. 4, pp. 469–474, July 2003.

[12] C. C. A. Rajan and M. R. Mohan, "An evolutionary programming-based tabu search method for solving the unit commitment problem," *IEEE Transactions on Power Systems*, vol. 19, no. 1, pp. 577–585, Feb 2004.

[13] C.-C. Su and Y.-Y. Hsu, "Fuzzy dynamic programming: an application to unit commitment," *IEEE Transactions on Power Systems*, vol. 6, no. 3, pp. 1231–1237, Aug 1991.

[14] P. K. Singhal, R. Naresh, and V. Sharma, "Binary fish swarm algorithm for profit-based unit commitment problem in competitive electricity market with ramp rate constraints," *IET Generation, Transmission Distribution*, vol. 9, no. 13, pp. 1697–1707, 2015.

[15] S. S. Reddy, P. R. Bijwe, and A. R. Abhyankar, "Optimal posturing in day-ahead market clearing for uncertainties considering anticipated real-time adjustment costs," *IEEE Systems Journal*, vol. 9, no. 1, pp. 177–190, March 2015.

[16] H. Pandi, T. Qiu, and D. S. Kirschen, "Comparison of state-of-the-art transmission constrained unit commitment formulations," in *2013 IEEE Power Energy Society General Meeting*, July 2013, pp. 1–5.

[17] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, and C. Singh, "The ieee reliability test system-1996. a report prepared by the reliability test system task force of the application of probability methods subcommittee," *IEEE Transactions on Power Systems*, vol. 14, no. 3, pp. 1010–1020, Aug 1999.