



Incorporating Wind Power Generation And Demand Response into Security-Constrained Unit Commitment

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ABSTRACT: Wind generation with an uncertain nature poses many challenges in grid integration and secure operation of power system. One of these operation problems is the unit commitment. Demand Response (DR) can be defined as the changes in electric usage by end-use customers from their normal consumption patterns in response to the changes in the price of electricity over time. Further, DR can be also defined as the incentive payments designed to induce lower electricity use at the times of high wholesale market prices or when system reliability is jeopardized. This paper presents a novel approach for incorporating stochastic wind power generation and DR with Security-Constrained Unit Commitment (SCUC) for improving the security and economic operation in power systems. DR is one of the methods of managing the economic filed in unit commitment. Demand includes the fixed and responsive loads, and the volatile nature of wind power is modeled. Responsive loads can be curtailed or shifted to another off peak hours. The combination of wind power generation and DR to SCUC problem makes a large scale optimization problem which needs a heavy mathematical computation and time consuming process. So, benders decomposition technique is applied to reduce the volume of the computation and problem complexity. To reach a fast approach, a proposed statistical and probabilistic method for omitting infeasible terms is used. Numerical simulation and final results on a modified IEEE 6- and 118-bus systems show the performance and effectiveness of the proposed approach.

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1- Introduction

1- 1- Restructured power market

Ensuring a secure and economical operation has two objectives in the restructured power market. In a secure power market, for reducing the cost of electricity utilization, appropriate strategies must be design. Market entities would be divided into independent system operator (ISO) and market participant [1]. The ISO would coordinate long-term planning by administrating transmission tariffs and maintaining system security [1]. In general, the role of ISO is to commit or to dispatch some or all of the power generated by the unit and curtailing loads for system security. Also, ISO, by sending appropriate economic signals to all market participants, should motivate them to investigate in the market [2, 3]. Market prepares a structure between buyers and sellers by a centralized approach to trade energy. The energy market prices should be reliable for market participants, financial markets and customers [4-5].

1- 2- Demand response

For supplying hourly forecast load, GENCOs submits their bids to ISO. According to the last scheduled generation unit, the market price would be cleared [6]. The demand side has now participated in this market that leads to the congested transmission lines, high operational cost, high fuel consumption and volatile market prices [7]. With no participation of the demand side in the market clearing process, unit bids might be much higher than the real production cost. This makes a market with volatile price and no competition [8]. For satisfying loads in absence of

reserve at peak hours, generators with high marginal cost should be used. In such a structure, demand side participation is a good economic method for prevailing constraint and freeing transmission capacity [9]. Increasing demand side participation could reduce volatile market prices, operating cost and also could benefit whole customer and electricity market participant [10], [11]. In this paper, we consider DR as a part of demand side management. In fact, DR is the load shifting or curtailment in reaction of high price or encouragement of market that includes emergency DR and economical DR. Voluntarily curtailment of loads in response to the market price is called economical DR [12]. Customers in restructured power system should set their consumption profile in response to the nodal price which differs with location and time [13]. However, instead of load curtailment, customers could also shift their load to off peak hours with cheaper price. All customers would benefit from cheaper market price that is the result of load curtailment in peak hours or shifting loads to off peak hour that makes a flat load profile [14].

1- 3- SCUC

SCUC is an optimization problem that minimizes operational costs, according to the submitted generation bids. The main objective of SCUC is obtaining a unit commitment schedule at minimum cost. Adequacy and security are two factors that by which reliability has been defined. The amount of available capacity resources must be adequate (adequacy), and on a daily or hourly schedule a system must be able to bear changes and contingencies (security). By using SCUC algorithm, ISO defines the day-ahead schedule in a restructured power market. However, the satisfying system

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constraint becomes more difficult, if most of the committed unit is located at on region. So, ISO incorporates alternative network constraint in unit commitment to minimize the operation cost and violation [1], [15].

1- 4- Wind power generation

Nowadays, wind power has an increasing share in power generation. Being clean and cheap is one of the reasons that countries trended toward. Variable, volatile and intermittent nature of wind makes its penetration a great challenge in power system scheduling [16]. The system should be scheduled in such a structure that the unit can easily be accommodated with the volatile nature of wind. These are the reasons why we should model the frequency and volatility of wind power. Weather data, statistical method and power-speed curve obtained from wind turbine are used for modeling wind generation that is a complex issue [17-18].

An evaluation process based on a stochastic UC model with unified power flow controller (UPFC) and uncertain wind power has been proposed in [19]. In this reference, a comprehensive evaluation process based on a two-stage stochastic UC model with UPFC and wind power integration is proposed. ISO day-ahead scheduling UC under uncertain conditions with DR is considered in [20]. Two kinds of DR, incentive-based DR and price-based DR are both incorporated according to their response characteristics. A bi-level two-stage stochastic security-constrained unit commitment model is proposed for this programmer to minimize the ISO cost considering the uncertain wind power output and the uncertain price elasticity [20]. Probabilistic UC problem presented in [21] gives the ISO a better source to make the right judgement to optimize the ancillary services usage in the system. The problem solved in this reference also gives the complete objective of a power system which is planning to incorporate Demand Response, Energy Storage and wind energy into their grid. Authors in [22] presented a congestion risk-aware UC formulation in a two-settlement market environment. In this reference, the uncertainty impact of multi-correlated wind power and contingencies on the risk of transmission congestion for each line is incorporated using basic statistical data on nodal wind power forecast and probability of credible line outages across the system. In [23], a newly distributed robust optimization framework for UC under uncertain wind power was provided. The proposed framework minimizes the worst-case expected total cost over an ambiguity set of possible probability distributions.

In this paper, the responsive loads as one part of DR can be curtailed and their characteristics are submitted to the ISO. Also, an hourly SCUC by considering the feasibility and contingencies for the market clearing process is applied.

1- 5- Article organization

Other parts of this paper are organized as follows: Section 2 presents the market clearing model and scenario generation. Section 3 includes problem formulation. Section 4 provides case studies and observations. The conclusion is investigated in section 5.

2- Market clearing model and scenario generation

Combination of wind power generation and DR in a restructured power market is presented in this section.

2- 1- Market clearing process

In restructured power markets, planning resources should be done for each hour of the day-ahead market. GENCOs can

affect on pricing and the amount of available electricity. A competitive power market could make a choice for customers and prevent monopoly [1]. For insuring reliability of power systems in real-time, generation and consumption should be balanced. When the market schedule is cleared, generation, transmission and load value changes and real-time market for power balancing should be established. Social welfare as an objective function of the hourly SCUC problem should be maximized, that is equal to: consumption payments of each load at each hour mines production cost of the system. We suppose GENCOs and loads submit their bids to the ISO for market clearing price. However, day-ahead market clearing price is cleared first, for ancillary services, bids are submitted [3, 5].

2- 2- Submitted load bids

DR is composed of the fixed and responsive loads. Fixed loads prices are cleared in the market process. By increasing demand, price of responsive loads will drop. Subjected constraints for responsive loads are shown as follows. Minimum down/up time presents the number of uninterrupted hours that loads should be off or restored. Load pickup/drop rate defines ramping that loads can be curtailed or restored. Minimum load curtailment shows the lower limit of load curtailment at each bus. Maximum daily curtailment defines the upper band of load curtailment in a day [9].

2- 3- Scenario generation

For considering volatile nature of wind power, normal distribution $N(\mu, \sigma^2)$ with the average of μ and standard deviation of σ^2 is used. We can also use other statistical distribution method for normalizing wind power generation. For the subjecting scenario to the normal distribution, Monte Carlo simulation is applied to generate scenarios. Based on the forecast wind power, a large number of random scenarios will be generated. We also use Latin hypercube sampling (LHS) for decreasing the variety of generated scenarios. LHS tries to find precise random distribution by reducing the number of generated scenarios simulated by Monte Carlo [24]. This technique is also profitable for decreasing computational time of scenario simulation. Based on the probability function, this decrement process measures the distance between scenarios and omits those with low probability [25, 26].

2- 4- Solution of SCUC including wind power and DR

Combination of SCUC problem with stochastic wind power generation and DR makes a mixed integer non-linear optimization problem on a large scale. Satisfying all constraints makes it too complicated and impossible to solve. For solving this problem, benders decomposition technique is applied. This approach will solve unit commitment in master problem by considering network control that determines the unit schedule in the base case. Without considering transmission and expected unserved energy (EUE) constraint, unit commitment will be omitting network violation or minimize EUE. Solution of master problem is used for checking feasibility, transmission constraint and wind accommodation in sub problems. By considering transmission constraint, wind power should be accommodated to the unit commitment by minimizing the congestion or maximizing reliability. According to the occurred violation, benders cut will be added to the master problem in the next iteration. For satisfying constraint, this iterative process continues until an optimal solution is found. The structure of this approach is depicted in Fig. 1 [1, 27].

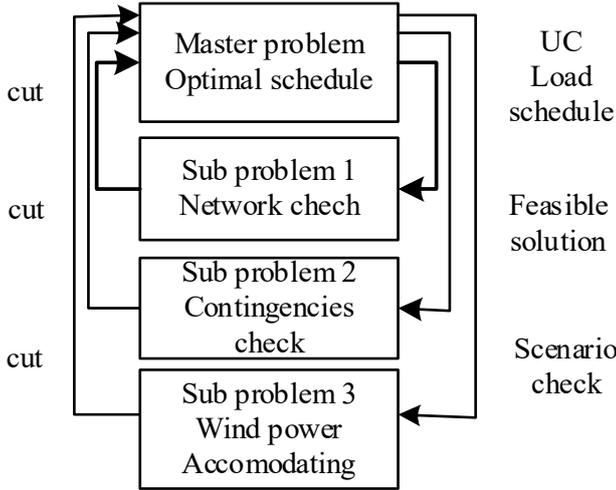


Fig. 1. Solution of SCUC problem with benders decomposition

3- SCUC Formulation With Wind Power Generation And DR
Formulation of SCUC with benders decomposition technique in master problem and sub problems, with related constraints are shown in the following.

3- 1- Master problem

Objective function (1), in master problem is composed of generation cost and consumption payment. These terms show the benefit that costumers earn from load curtailment mines generation cost.

$$Max \left\{ \sum_{t=1}^{NT} \sum_{b=1}^{NB} CB_{bt} (D_{bt}) - \sum_{t=1}^{NT} \sum_{i=1}^{NG} [F_{ci} (P_{it}) * I_{it} + SU_{it} + SD_{it}] \right\} \quad (1)$$

3- 2- System constraints

Power balance (2): generated power must be equal to the demand consumption plus network losses. The system is spinning and operating reserve (3), (4): these constraints are applied to guarantee power absence at peak hours or system outage. Ram up/down limit (5), (6): units should change their production level according to this ramp rate. Minimum on/off time (7), (8): these constraints impose to restrict unit on/off time. It means that when a unit changes its status, it must stay in a new mode for a specified time. Power generation limit (9): this constraint limits the maximum and minimum power generation of each unit [1], [22].

$$\sum_{i=1}^{NG} P_{it} * I_{it} + \sum_{i=1}^{NW} P_{W,it}^f = \sum_{b=1}^{NB} D_{bt} + P_{L,t} \quad (t = 1, 2, \dots, NT) \quad (2)$$

$$\sum_{i=1}^{NG} R_{S,it} * I_{it} \geq R_{S,t} \quad (t = 1, 2, \dots, NT) \quad (3)$$

$$\sum_{i=1}^{NG} R_{o,it} * I_{it} \geq R_{o,t} \quad (t = 1, 2, \dots, NT) \quad (4)$$

$$P_{it} - P_{i(t-1)} \leq [1 - I_{it} (1 - I_{i(t-1)})] UR_i + I_{it} (1 - I_{i(t-1)}) P_{i,min} \quad (i = 1, 2, \dots, NG; t = 1, 2, \dots, NT) \quad (5)$$

$$P_{i(t-1)} - P_{it} \leq [1 - I_{i(t-1)} (1 - I_{it})] DR_i + I_{i(t-1)} (1 - I_{it}) P_{i,min} \quad (i = 1, 2, \dots, NG; t = 1, 2, \dots, NT) \quad (6)$$

$$[X_{i(t-1)}^{on} - T_i^{on}] [I_{i(t-1)} - I_{it}] \geq 0 \quad (i = 1, 2, \dots, NG; t = 1, 2, \dots, NT) \quad (7)$$

$$[X_{i(t-1)}^{off} - T_i^{off}] [I_{it} - I_{i(t-1)}] \geq 0 \quad (i = 1, 2, \dots, NG; t = 1, 2, \dots, NT) \quad (8)$$

$$P_{i,min} * I_{it} \leq P_{it} \leq P_{i,max} * I_{it} \quad (i = 1, 2, \dots, NG; t = 1, 2, \dots, NT) \quad (9)$$

3- 3- Scenario constraint

Scenario power balance (10): in each scenario summation of generation power, demand consumption and system losses must be equal to zero. Scenario spinning and operating reserve (11), (12), permissible adjustment of real power generation (13) and constraint (14) that restrict power generation in scenarios [26].

$$\sum_{i=1}^{NG} P_{it}^s * I_{it} + \sum_{i=1}^{NW} P_{W,it}^s = \sum_{b=1}^{NB} D_{bt} + P_{L,t} \quad (t = 1, 2, \dots, NT) \quad (10)$$

$$\sum_{i=1}^{NG} R_{S,it}^s * I_{it} \geq R_{S,t} \quad (t = 1, 2, \dots, NT) \quad (11)$$

$$\sum_{i=1}^{NG} R_{o,it}^s * I_{it} \geq R_{o,t} \quad (t = 1, 2, \dots, NT) \quad (12)$$

$$|P_{it}^s - P_{it}| \leq \Delta_i \quad (i = 1, 2, \dots, NG; t = 1, 2, \dots, NT) \quad (13)$$

$$P_{i,min} * I_{it} \leq P_{it}^s \leq P_{i,max} * I_{it} \quad (i = 1, 2, \dots, NG; t = 1, 2, \dots, NT) \quad (14)$$

3- 4- Load constraint

For load participation, these constraints should be imposed to the problem. Bus load (15), total load at each bus is composed of fixed and responsive loads that must be equal to the summation of total load. Minimum load curtailment (16), curtailed loads less than this amount, could not participate in the program. In this case, instead of the scheduled responsive load, the amount of responsive load mines, curtailed load, would participate in the program. Nonnegative responsive load (17), this constraint should be imposed to ensure that curtailed load is larger than minimum load curtailment. Submitted responsive load (18), if loads do not curtail, the submitted responsive load should be scheduled. Ramp up/down limit of loads (19), (20), loads should change their consumption level according to this ramp rate. Minimum on/off time of loads (21), (22), we have also this constraint to restrict loads curtailing or restoring. And the last loads constraint is daily load curtailment (23), total load curtailment in each day should be lower than the pre-specified amount [28].

$$D_{bt} = D_{bt}^f + D_{bt}^r \quad (b = 1, 2, \dots, NB; t = 1, 2, \dots, NT) \quad (15)$$

$$[D_{bt}^{r,max} - DX_{bt}^{min} - D_{bt}^r] v_{bt} \geq 0 \quad (b = 1, 2, \dots, NB; t = 1, 2, \dots, NT) \quad (16)$$

$$D_{bt}^r v_{bt} \geq 0 \quad (b = 1, 2, \dots, NB; t = 1, 2, \dots, NT) \quad (17)$$

$$[D_{bt}^r - D_{bt}^{r,max}] [1 - v_{bt}] \geq 0 \quad (b = 1, 2, \dots, NB; t = 1, 2, \dots, NT) \quad (18)$$

$$D_{bt}^r - D_{b(t-1)}^r \leq UR_b \quad (b = 1, 2, \dots, NB; t = 1, 2, \dots, NT) \quad (19)$$

$$D_{b(t-1)}^r - D_{bt}^r \leq DR_b \quad (b = 1, 2, \dots, NB; t = 1, 2, \dots, NT) \quad (20)$$

$$\begin{aligned} [X_{b(t-1)}^{on} - UT_b] [v_{b(t-1)} - v_{bt}] &\geq 0 \\ (b = 1, 2, \dots, NB; t = 1, 2, \dots, NT) \end{aligned} \quad (21)$$

$$\begin{aligned} [X_{b(t-1)}^{off} - DT_b] [v_{bt} - v_{b(t-1)}] &\geq 0 \\ (b = 1, 2, \dots, NB; t = 1, 2, \dots, NT) \end{aligned} \quad (22)$$

$$\sum_{t=1}^{NT} (D_{bt}^{r,max} - D_{bt}^r) \leq EX_b^{max} \quad (b = 1, 2, \dots, NB) \quad (23)$$

3- 5- Sub Problem And Benders Decomposition

3- 5- 1- Feasibility And Contingencies Check

Solving this SCUC problem is a time consuming process and by incorporating stochastic wind power, and DR becomes so complicated. Therefore, benders decomposition technique is applied for decomposing the problem into master problem and sub problems. Unit commitment for determining the unit schedule and power generation are solved in master problem. This solution for feasibility and contingencies is checked and also scenario accommodating is given to the sub problems. If any violations occurred, hourly cuts (24) and (25) for system security will be added to master problem in next iteration. In sub problem, power mismatch tried to be minimized in all buses [1, 27 - 28].

$$\hat{w}_t + \sum_{i=1}^{NG} \pi_{it} (P_{it} I_{it} - \hat{P}_{it} \hat{I}_{it}) + \sum_{b=1}^{NB} \mu_{bt} (D_{bt} - \hat{D}_{bt}) \leq 0 \quad (24)$$

(t = 1, 2, \dots, NT)

$$\hat{w}_t + \sum_{i=1}^{NG} (\bar{\pi}_{it} - \underline{\pi}_{it}) (P_{it} - \hat{P}_{it}) + \sum_{b=1}^{NB} \mu_{bt} (D_{bt} - \hat{D}_{bt}) \leq 0 \quad (25)$$

(t = 1, 2, \dots, NT)

Here, \hat{w}_t shows power mismatch in base case for current bus. π_{it} , μ_{bt} , $\bar{\pi}_{it}$ and $\underline{\pi}_{it}$ are dual variables of hourly dispatch, load balance equations and hourly generation constraint.

3- 5- 2- Feasibility Check Sub Problem In Scenario

Non-negative slack variables for minimizing wind power violation in each scenario are added to the related constraints. Here, v^s is the summation of this added slack variable in scenarios that must be minimized. Positive value obtained by this term shows that unit commitment and power dispatch in master problem cannot be accommodated with the forecast wind power in scenarios. Therefore, benders cut (26) is added to master problem in the next iteration for mitigating this violation [29].

$$v^s(P) = v^s + \sum_{i=1}^{NG} \sum_{t=1}^{NT} \left(\frac{\partial v^s}{\partial P_{it}} | \hat{P}_{it} \right) (P_{it} - \hat{P}_{it}) \leq 0 \quad (26)$$

4- Case Studies And Numerical Simulation

Modified IEEE 6-bus and 118-bus systems are used for analyzing the proposed algorithm. The system data are available on <http://motor.ece.iit.edu.data> and www.ieee.hr. For solving this problem, this given information is used: In each bus ten percent of the total load supposed to be responsive, consumption bid 20\$/MWH, minimum hourly

load curtailment at each bus 5MW and maximum load curtailment 150 mw of a day [28]. Wind price is zero and reserve requirement stay the same during wind penetration. Also, these three scenarios are considered: SCUC in the base case, SCUC with DR and SCUC with DR and stochastic wind power generation.

4- 1- IEEE 6-bus system

The structure of this system is shown in Fig. 2. This system includes 3 generation units, 7 transmission lines and two transformers.

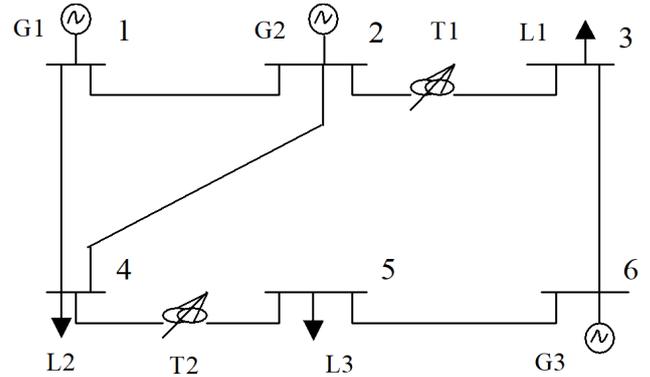


Fig. 2. Structure of 6-bus system in base case.

4- 1- 1- SCUC in the base case

By running the SCUC in the base case, the total operation cost is obtained 137491.924\$ with the computational time of 3 minute. The three generation units participate in load satisfying programs. Unit number 1 participates in the all-time of the day, unit number 2 participates is 10 hours, and unit number 3 participates in 17 hours. Power generation by each unit is shown in Fig. 3. According to this figure, at the beginning of the day that demand is low, the only active unit is unit one. By increasing demand, unit 1 increases its generation level to the maximum limit and other unit also would be commitment. Total operational hours for three units are 51 hours in this case.

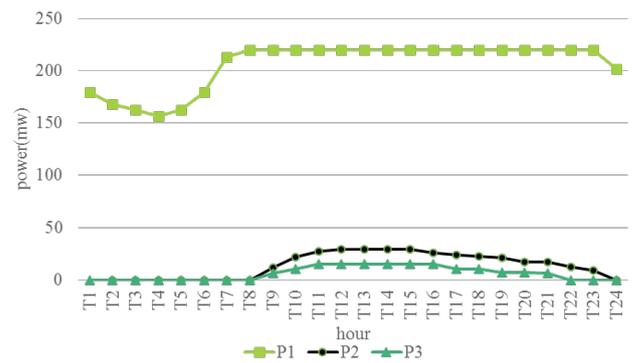


Fig. 3. Power generation for 6-bus at base case.

4- 1- 2- SCUC with DR

In this case, 10% of the total load in each bus is responsive and the rest is fixed. Responsive loads are those that can be curtailed or shifted to other operational hours in the response of the system price or security. Computed operation cost with DR is 124421.209\$ and the run program time is 5 minutes. By comparing the result with the base case, there

is 1307.715\$ reduction. The three units participated in the power production are depicted in Fig. 4. Similar to the base case, unit 1 is on for 24 hours, but the committed state of unit 2 decreases to 8 and unit 3 to 16 hours. Also, production level of these two units decreases to lower range, this reduction is because of demand decrement at peak hours that need lower power generation and fewer status changes. Total operational hours are decreased in comparison of base case to 48 hours. This reduction is the result of using DR.

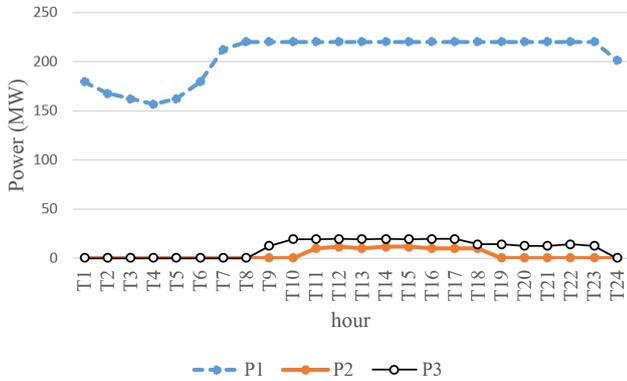


Fig. 4. Power generation with DR for 6-bus.

After solving SCUC problem, status of load and their curtailment is cleared. Table 1 shows the remaining responsive load, after participating in the load curtailment program. Here, the variation of responsive load amplitudes is between 0 to 10% of total load at each bus, 0 show the fully curtailment of this responsive load at the right time.

Table 1. Responsive load participation in program.

hour	T1	T2	T3	T4	T5	T6	T7	T8
B3	3.584	3.36	3.248	3.136	3.136	3.248	3.548	4.258
B4	7.168	6.72	6.496	6.272	6.272	6.49	7.168	8.512
B5	7.168	6.72	6.496	6.272	6.272	6.49	7.168	8.512
hour	T9	T10	T11	T12	T13	T14	T15	T16
B3	4.872	0.116	0	0	0	0	0	0
B4	9.744	0.139	0	0	0	0	0	0
B5	4.744	0.345	0	0	0	0	0	0
hour	T17	T18	T19	T20	T21	T22	T23	T24
B3	0	0	0	0	0	0	4.872	4.032
B4	0	0	0	0	0	0	1.21	8.064
B5	0	0	0	0	0	0	4.678	8.064

Effect of DR on the network load profile before (D1) and after combination (D2) of DR with SCUC is given in Table 2. Also, for better comparison, Fig. 5 shows the effect of load curtailment on curving demand at peak hour. At hours 1-9, there is no load curtailment, so D1 is equal to D2.

Table 2. DR effect on demand reduction.

hour	T1	T2	T3	T4	T5	T6	T7	T8
D1(MW)	175.19	165.15	158.67	154.73	155.06	160.48	173.39	177.6
D2(MW)	175.19	165.15	158.67	154.73	155.06	160.48	173.39	177.6
DR(MW)	17.92	16.8	16.24	15.68	15.68	16.24	17.92	21.28
hour	T9	T10	T11	T12	T13	T14	T15	T16
D1(MW)	186.81	206.96	228.61	236.1	242.18	243.6	248.86	255.79
D2(MW)	186.81	204.86	203.662	210.9	217.232	218.4	223.66	231.346
DR(MW)	23.86	23.997	24.948	25.2	24.948	25.2	25.2	24.443
hour	T17	T18	T19	T20	T21	T22	T23	T24
D1(MW)	256	246.74	245.97	237.35	237.31	232.67	195.91	195.6
D2(MW)	231.808	222.548	222.534	214.166	214.126	209.236	172.93	175.44
DR(MW)	24.192	24.192	23.436	23.184	23.184	23.436	23	20.16

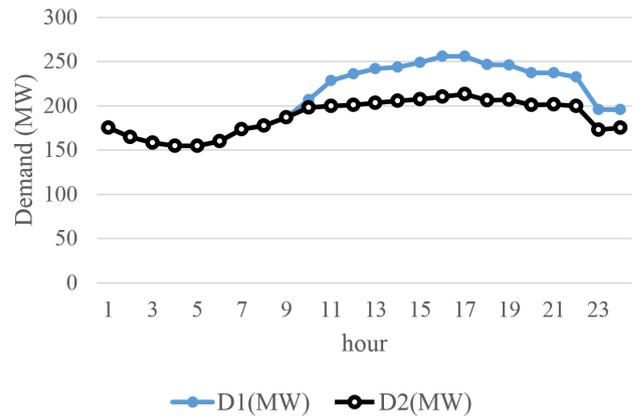


Fig. 5. Demand curtailment by DR incorporation.

4- 1- 3- SCUC with DR and stochastic wind power generation
 Wind power as one of the distributed generation resources is incorporated in SCUC problem for reducing operational cost and improving system operation. Ten generated scenarios are considered for modeling the probabilistic nature of wind power generation. These scenarios are produced according to the obtained data from wind farms and weather forecasting. Operational cost is obtained 104226.506\$ in this scenario that has a 33265.48\$ reduction in comparison with the base scenario and 20194.703\$ reduction in comparison to the second scenario. The computational time of this scenario is 9 minutes. By considering wind power, commitment state changes and unit numbered 3 would turn off in whole scenario. Like two other scenarios, unit one became on, but its production level decreased to lower level. Commitment states for unit 2 is as follows: whole time for first 6 scenarios, 3 hours in 7th scenario, 2 hours in 8th scenario and 1 hour for scenarios 9th and 10th. The unit production decreases to lower level and units with high marginal cost will be off by increasing wind power ratio. Here, two scenarios were chosen for more analysis. The amount of power generation in first and 7th scenarios are respectively shown in Table 3 and Table 4.

Table 3. Power generation in first scenario

hour	T1	T2	T3	T4	T5	T6	T7	T8
P11	119.2	110	105.4	100.8	100.8	106.4	123.2	156.8
P21	10	10	10	10	10	10	10	10
P31	0	0	0	0	0	0	0	0
hour	T9	T10	T11	T12	T13	T14	T15	T16
P11	187.6	201.5	206.7	209	207.7	209	209	200.6
P21	10	10	10	10	10	10	10	10
P31	0	0	0	0	0	0	0	0
hour	T17	T18	T19	T20	T21	T22	T23	T24
P11	197.8	197.8	189.4	188.6	188.6	189.4	177.6	145.6
P21	10	10	10	10	10	10	10	10
P31	0	0	0	0	0	0	0	0

As it is observed from the above tables, unit power production decreases by increasing wind power penetration. But unit 1 produces power at its highest range. This power absence would be compensated by wind power generation. Fig. 6 and Fig. 7 show the distributed power generation in each scenario for different hours, respectively. P11 and P17 are power generation in first and 7th scenarios by the unit one, respectively.

Table 4. Power generation in 7th scenario

hour	T1	T2	T3	T4	T5	T6	T7	T8
P17	116.6	108.5	107	96	98.7	103.2	112.6	148.1
P27	10	10	10	0	0	0	0	0
P37	0	0	0	0	0	0	0	0
hour	T9	T10	T11	T12	T13	T14	T15	T16
P17	176.5	195.2	196.4	203	205	207	207	198.6
P27	0	0	0	0	0	0	0	0
P37	0	0	0	0	0	0	0	0
hour	T17	T18	T19	T20	T21	T22	T23	T24
P17	194.5	193.2	181.2	179.3	178.5	175	172	145.6
P27	0	0	0	0	0	0	0	0
P37	0	0	0	0	0	0	0	0

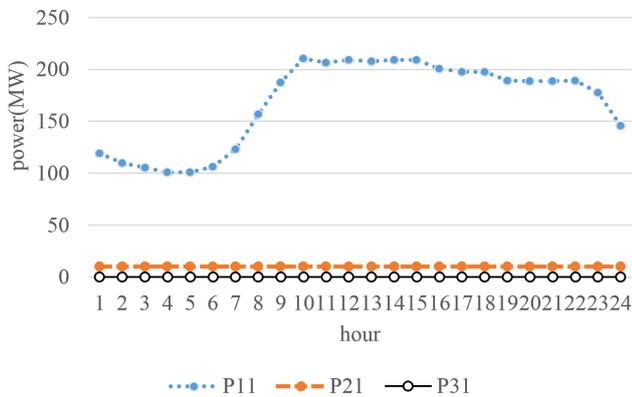


Fig. 6. Distribution of power generation in first scenario.

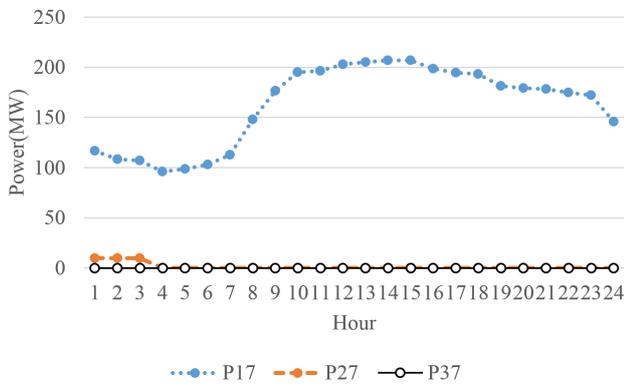


Fig. 7. Distribution of power generation in 7th scenario.

Incorporating wind power into SCUC problem also has its effect on DR and load curtailment. For better comparison, the participation of DR in presence of wind power is shown in Table 5 and Fig. 8. Here, D1 is the demand before a combination of DR and wind power. D2 is the demand after combination of DR. Also, DR1 and DR7 shows demand after combination of DR and wind power generation in first and 7th scenarios, respectively. The numbers show the amount of the remaining demand in different cases of program.

4- 2- IEEE 118-bus system

For a better illustration, this test is also done on IEEE 118-bus system. System characteristics are as follows: 54 generation unit, 9 tap-changers, 186 lines and maximum demand of 6000 MW a day. Total operating cost after solving SCUC problem in the absence of DR and wind power obtained 1,067,031.191\$.

Table 5. DR effect on demand reduction.

hour	T1	T2	T3	T4	T5	T6	T7	T8
D1(MW)	175.19	165.15	158.67	154.73	155.06	160.48	173.39	177.6
D2(MW)	175.19	165.15	158.67	154.73	155.06	160.48	173.39	177.6
DR1(MW)	175.19	165.15	158.67	154.73	155.06	160.48	173.39	177.6
DR7(MW)	175.19	165.15	158.67	154.73	155.06	160.48	173.39	177.6
hour	T9	T10	T11	T12	T13	T14	T15	T16
D1(MW)	186.81	206.96	228.61	236.1	242.18	243.6	248.86	255.79
D2(MW)	186.81	204.86	203.662	210.9	217.232	218.4	223.66	231.346
DR1(MW)	186.81	194.01	200.894	202.36	205.959	206.4	207.66	210.507
DR7(MW)	186.31	204.565	198.382	204.9	205.323	206.4	207.66	201.507
hour	T17	T18	T19	T20	T21	T22	T23	T24
D1(MW)	256	246.74	245.97	237.35	237.31	232.67	195.91	195.6
D2(MW)	231.808	222.548	222.534	214.166	214.126	209.236	172.93	175.44
DR1(MW)	208.826	211.429	210.574	207.926	208.886	206.274	187.27	195.6
DR7(MW)	206.826	211.429	210.574	207.926	207.511	205.182	184.606	195.6

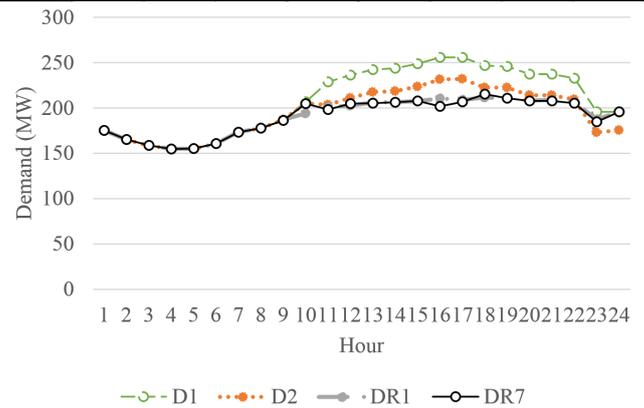


Fig. 8. Demand curtailing by DR incorporation and wind power

After incorporating DR by impact factor of 10%, operation cost is reduced to 1,049,223.153\$. Finally, solution of SCUC includes DR, and stochastic wind power generation decreases to 995,164.448\$ in last case. The proposed algorithm is applied to a 2.6 GHz computer using GAMS 23.3 [38].

5- Observation

A total comparison for all case studies is shown in Table 6, which represents the effectiveness of this approach in cost reduction. Some other benefits of the proposed method are: demand decrement at peak hours, reduction in operation cost, social welfare improvement and reduction in LMP.

Table 6. Total comparison

6-bus system	operational cost	cost reduction	time
SCUC in base case	137491.924\$	0\$	3 min
SCUC with DR	124421.209\$	13070.715\$	5 min
SCUC With DR and wind power	104226.506\$	33265.418\$	9 min
118-bus system	operational cost	cost reduction	time
SCUC in base case	1067031.191\$	0\$	67 min
SCUC with DR	1049223.153\$	17808.038\$	79 min
SCUC With DR and wind power	995164.448\$	71866.743\$	112 min

6- Conclusions

A novel approach for incorporating SCUC algorithm with DR and stochastic wind power generation is developed in this paper. Load curtailment at peak hours can reduce the operation cost and improve social welfare. Iterative process between master problem and sub problems can result in a robust SCUC for accommodating wind power and DR. Here, a spacious formulation for modeling SCUC with DR and

wind power is proposed. Generation units, loads and scenario constraint are considered in this algorithm. Numerical simulations on 6-bus and 118-bus system shows the benefits of SCUC combination with DR and wind power.

Indices:

- b index for buses.
- i index for unit.
- t index for time.

Sets:

- S superscript for scenario.
- f superscript for fixed loads.
- R superscript for responsive loads.

Parameters:

- NB number of buses.
- NG number of unit.
- NW number of wind power unit.
- NT number of period (hour).
- DR_i Ramp-down rate limit of unit i.
- UR_i Ramp-up rate limit of unit i.
- $R_{S,t}$ System spinning reserve at time t.
- $R_{S,t}^s$ System spinning reserve at time t in scenario s.
- $R_{O,t}$ System operating reserve at time t.
- $R_{O,t}^s$ System operating reserve at time t in scenario s.
- $R_{S,it}$ Spinning reserve of unit i at time t.
- $R_{S,it}^s$ Spinning reserve of unit i at time t in scenario s.
- $R_{O,it}$ Operating reserve of unit i at time t.
- $R_{O,it}^s$ Operating reserve of unit i at time t in scenario s.
- SU_{it} Startup cost of unit i at time t.
- SD_{it} Shutdown cost of unit i at time t.
- T_i^{off} Minimum off time of unit i.
- T_i^{on} Minimum on time of unit i.
- X_i^{off} Off time of unit i at time t.
- X_i^{on} On time of unit i at time t.
- EX_b^{max} Maximum load curtailment at bus b.
- D_{bt}^f Fixed load at bus b at time t.
- D_{bt}^r Responsive load at bus b at time t.
- D_{bt}^{max} Submitted responsive load at bus b at time t.
- DX_{bt}^{min} Minimum load curtailment at bus b at time t.
- DR_b Down-rate limit of load at bus b.
- UR_b Up-rate limit of load at bus b.
- UT_b Minimum on time of load at bus b at time t.
- DT_b Minimum off time of load at bus b at time t.
- X_{bt}^{on} On time of load at bus b at time t.
- X_{bt}^{off} Off time of load at bus b at time t.
- $P_{i,max}$ Lower real power generation of unit i.
- $P_{i,min}$ Upper real power generation limit of unit i.

Variables:

- F_{ci} Production cost function for unit i.
- I_{it} Commitment state of unit i at time t.
- $P_{W,it}^f$ Forecasted wind power of unit i at time t.
- $P_{W,it}^s$ Simulated wind power for unit i at time t in scenario s.
- P_{it}^s Power production of unit i at time t in scenario s.
- $P_{L,t}$ System losses at time t.
- P_{it} Power production of unit i at time t.
- Δ_i Permissible real power adjustment of unit i.
- CB_{bt} Consumption benefit at bus b at time t.
- D_{bt} Total load at bus b at time t.
- GC_{bt} Generation cost of unit i at time t.
- v_{bt} Curtailment state of load at bus b at time t.
- w_t Power mismatch at time t.
- μ_{bt}, π_{bt} Dual variable.

Symbols:

- \wedge Given variable.

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