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Unit Commitment in Power Market Considering Demand Response and Stochastic Wind Generation

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Abstract: ***Integration of wind units into power system introduce various sources of technical and economical challenges to operation of power system due to its inherent uncertainty and variability. In operation of power system, stochastic wind generation can affect on the system security. In this paper, optimal security-constrained unit commitment (SCUC) in presence of demand response program (DR) based on stochastic wind generation is proposed as a novel method of SCUC to address the mentioned concern. In order to secure system from stochastic wind generation, the SCUC results have to be valid for most probable wind generation scenarios. The problem is formulated as a mixed-integer programming (MIP) and solved using Benders decomposition which implemented using GAMS software (CPLEX solver). The results of applying proposed method on IEEE six-bus test system show that the proposed method can successfully find the optimal SCUC which satisfied all constraints while is secure against variations in wind generation.***

Keywords: Security-constraint unit commitment(SCUC), Stochastic wind generation, Demand response (DR), Benders decomposition.

Indices:

i , j	Index for bus.
K	Index for time.
S	Index for wind power generation scenario.
G	Index for generators.
NK,NI, NG	Number of time periods, buses and generation units of system.
$C(\mathrm{Pdf}_{ki}), C(Pdr_{ki})$	Revenue from constant load and responsive load, respectively.
$StCst$, $SdCst$	Start up and shut down cost of Unit g at Time k.
A	Supply bidding price of Unit g at Time k.
$C\min$	No load operation cost.
Pdf_{ki}	Non-responsive demand at Bus i at Time k.
$pwind_{kg}$	Wind farm generation at Bus i at Time k.
$Pdr\max_{ki}$	submitted responsive load at Bus i at Time k.
$Pdx\min_{ki}$	Minimum curtailable load at Bus i at Time k.
X_{ik}^{on} , X_{ik}^{off}	ON and OFF time of load at Bus i at Time t.
RU_i , RD_i	Pick up and drop off rate of load at Bus i.
$E\max_i$	Maximum daily curtailable load at Bus i.
SR_k	Required spinning reserve at Time t.
NSR_k	Required non-spinning reserve at Time k.
$pl\max_{kij}$	Maximum power transfer between Bus i and Bus j at Time k.
T_g^{off}	Minimum OFF time of Unit g.
T_g^{on}	Minimum ON time of Unit g.
RU_g , RD_g	Ramp-up rate and ramp-down limit of Unit g.
X_{kg}^{off}	OFF time of unit at Time k.
X_{kg}^{on}	ON time of unit at Time k.
$P\max_g$, $P\min_g$	Upper and lower limit of real power generation of Unit g.
$pwind_{kg}$	Forecasted generation of wind power Unit g at Time k.
$Pwind_{kg}^s$	Simulated generation of wind power Unit g at Time k in Scenario s.

QSC_{kg}	Quick start capability (QSC) of Unit g.
MSR_{kg}	Maximum sustained rate (MSR) of Unit g.
$Bline_{ij}$	Susceptance of Line ij.
$delta_{ki}$	Phase angle of Bus i at Time k.
Δ_g	Permissible real power adjustment of Unit g.
Pdr_{ki}	Responsive load at Bus i at Time t.
$U1_{kg}$	Start up state of Unit i at Time t.
$V1_{kg}$	Shut down state of Unit i at Time t.
PG_{kg}	Active generation of Unit g at Time t.
PSR_{kg}	Provided spinning reserved by Unit i at Time t.
$PNSR_{kg}$	Provided non-spinning reserved by Unit i at Time t.
$pline_{kij}$	active power flow between Bus i and Bus j at Time t.
W_{kg}	Binary variable which shows the state of generation units of Bus i at Time t.
M_{ki}	Binary variables for DR which shows the state of load of Bus i at Time t.

I. Introduction

In restructured power system, security constrained unit commitment (SCUC) deals with generation schedule to satisfy the hourly system load while maintaining system security at the maximum social welfare. In recent years, installed wind capacity has been rapidly increased due its clean and indigenous nature. However, this capacity is not readily dispatched due to its intermittent nature. The variation and uncertainty of wind power generation impact power system characteristics such as frequency and generation adequacy which can reduce the reliability of power system. In [1] a SCUC algorithm for considering the uncertainty of wind power generation is presented. The UC problem is solved in the master problem with the forecasted wind power generation. Then initial dispatch is checked in the subproblem considering simulated possible scenarios for representing the wind power volatility.

Reference [2] investigates the uncertainty in the prediction of wind units in the UC problem and economic dispatch. It shows that representing uncertainty in the wind power forecasting with wind power scenarios that rely on stochastic UC has advantages over deterministic approaches that mimic the classical models.

The scenario-based approach and the interval optimization approach for the Stochastic SCUC solution with the consideration of uncertain wind power generation are investigated in [3]. Uncertainty of wind units using these two methods has been modeled and results obtained from these two methods are compared.

A SCUC approach with uncertain wind power generation is presented in [4] which the computational burden associated with the calculation of the reserve deployment for each scenario is reduced remarkably.

A two-stage stochastic SCUC with a scenario selection algorithm for choosing and weighing wind power generation scenarios and composite component failures is presented in [5].

A two-stage adaptive robust SCUC model with uncertain demand and wind power generation at the individual nodal level is proposed in [6]. A combination of Benders decomposition type algorithm and the outer approximation technique are used for solving the problem.

With the recent progress in power system, different approaches such as compressed air energy storage [7] , hybrid vehicles [8] , hydrogen storage [9], and demand response (DR) [11 , 10] for managing intermittency and volatility of wind power generation and reducing the operation cost have been proposed. In this paper, DR is considered as a potential solution for the reliable integration of wind generation resources into power system operations. Load serving entity acts as an customer loads aggregator and provides the load data to the independent system operator(ISO). The ISO runs SCUC based on the available data generating units and transmission lines information as well as wind power forecast and possible wind power scenarios incorporates DR into the market clearing process to obtain the efficient market.

The rest of this paper is organized as follows. Section II presents SCUC model with DR and wind power generation and formulates the problem. The simulation results are provided in Section III and the paper is concluded in Section IV.

II. SCUC with hourly DR considering stochastic wind power generation

The proposed SCUC with hourly DR applied for market clearing is presented in this section.

A. Market clearing process

The general model of the target market is as follows: wind farm owners submit their hourly wind power forecast for 24 hours day ahead to the ISO, and the operating costs of wind units are assumed to be zero. The ISO receives transmission lines information from transmission companies, and transmission constraints are considered in the base case and contingencies. It is assumed that both generation companies and load serving entities could submit complex offers and bids to the ISO. The data from generation companies includes hourly quantity and price of power, unit ramping up limits, unit ramping down limits, unit minimum ON time limits, unit minimum OFF time limits, and unit generation limits. Load serving entities bids consist of fixed and responsive load bids. Fixed loads are expected to be fully met and will be treated in accordance with the market-clearing price. Responsive load bids include hourly quantity and price of load along with minimum ON/OFF time limits, recovery/loss rates, minimum hourly curtailment, and maximum daily curtailment are submitted to the ISO. Then The SCUC schedule for complex bids and wind generation scenarios would demonstrate the optimal commitment and dispatch of generating units and the hourly DR based on submitted offers and bids.

B. Wind power and demand scenario generation and reduction

To model the uncertainty of wind power and demand, in this paper wind power and demand are assumed as normal distribution, and we use the concept of net demand. The net demand (ND) is the difference between the demand and the wind power forecasts [11, 12]:

ND^{f} = *demand - wind power forecast* = ND^{mean} + *net demand forecast error* (1)

In this case, assuming no correlation between demand and wind forecast errors, the standard deviation of the net load is given as follows

$$\delta_{NL} = \sqrt{\delta_L^2 + \delta_N^2} \tag{2}$$

Here, Monte Carlo method is used to generate a large number of scenarios subject to a normal distribution [1]. However, we should use scenario reduction method due to time limitation and low probability of most of the scenarios. Using this method, the problem would be solved only for cases that have more probability to happen in normal operation of power system.

C . Formulation of SCUC with DR

The objective of the SCUC problem is to determine the day-ahead schedule of generating units and loads with the aim of maximizing the system social welfare while respecting the unit, load and system constraints. The objective shown in (3) is the consumption benefit minus the generation cost, and startup and shutdown costs of individual units over the scheduling horizon.

$$Max \sum_{K=1}^{NK}\sum_{i=1}^{NL}[C\,(\mathrm{Pdf}_{ki} + Pdr_{ki})] - \sum_{k=1}^{NK}\sum_{g=1}^{NG}[(StCst * U1_{kg}) + (SdCst * V1_{kg}) + (C\min * W_{kg}) + (A * PG_{kg})] \tag{3}$$

The hourly SCUC is subjected to the following constraints:

Equation (4) depicts the system energy balance for each bus at all time. Pdr_{ki} is the responsive load which can be changed in order to decrease the system cost or balancing the generation versus load. The responsive load cannot be negative and the amount of curtailed load cannot be less than its minimum curtailment rate. These facts are modeled in (5) and (6). Equation (7) will shift the load when load should be curtailed and/or when the energy price is high to another time horizon. Constraints (8) and (9) would limit hourly load pickup and pick drop, respectively. Equations (10) and (11) impose the minimum number of time which load cannot be curtailed or restored. In addition, the amount of active power which can be curtailed cannot be higher than it's limit which is imposed by (12).

$$\sum_{g=1}^{NG} PG_{kg} * W_{kg} + \sum_{g=1}^{NW} pwind_{kg} - \sum_{i=1}^{NI}(Pdf_{ki} + Pdr_{ki}) = 0$$

$$k = 1, \dots, \mathrm{NK} \tag{4}$$

$$[Pdr\max_{ki} - Pdx\min_{ki} - Pdr_{ki}]M_{ki} \ge 0$$

$$i = 1, \dots, NI;\, k = 1, \dots, NK \tag{5}$$

$$Pdr_{ki}M_{ki} \ge 0$$

$$i = 1, \dots, NI;\, k = 1, \dots, NK \tag{6}$$

$$Pdr_{ki}M_{ki} \ge 0$$

$$i = 1, \dots, NI;\, k = 1, \dots, NK \tag{7}$$

$$[Pdr_{ki} - Pdr\max_{ki}][1 - M_{ki}] \ge 0$$

$$i = 1, \dots, NI;\, k = 1, \dots, NK \tag{8}$$

$$Pdr_{ki} - Pdr_{(k-1)i} \le RU_i$$

$$i = 1, \dots, NI;\, k = 1, \dots, NK \tag{9}$$

$$Pdr_{(k-1)i} - Pdr_{ki} \le RD_i$$

$$[X_{i(k-1)}^{on} - UT_i][M_{i(k-1)} - M_{ik}] \ge 0$$

$$i = 1, \dots, NI;\, k = 1, \dots, NK \tag{10}$$

$$[X_{i(k-1)}^{off} - DT_k][M_{ik} - M_{i(k-1)}] \ge 0$$

$$i = 1, \dots, NI;\, k = 1, \dots, NK \tag{11}$$

$$\sum_{k=1}^{NK}(Pdr\max_{ki} - Pdr_{ki}) \le E\max_i$$

$$i = 1, \dots, NI \tag{12}$$

$$\sum_{g=1}^{NG} PSR_{kg} * W_{kg} \ge SR_k$$

$$k = 1, \dots, NK \tag{13}$$

$$PSR_{kg} \le 10 * MSR_{kg} * W_{kg} \tag{14}$$

System operating reserve requirements:

$$\sum_{g=1}^{NG} PNSR_{kg} * W_{kg} \ge NSR_k$$

$$k = 1, \dots, NK \tag{15}$$

$$PNSR_{kg} \le QSC_{kg} \tag{16}$$

The maximum sustained rate (MSR) and the quick start capability (QSC) are used to limit the spinning and operating reserves of the unit, respectively. Unit's operating reserve is the same as spinning reserve, when a unit is ON. When a unit is OFF, its operating reserve is equal to its QSC.

Unit ramping up limit:

$$PG_{kg} - PG_{(k-1)g} \le [1 - W_{kg}(1 - W_{(k-1)g})]RU_g + W_{kg}(1 - W_{(k-1)g})P\min_g$$
$$g = 1,...,NG; k = 1,...,NK \quad (17)$$

Unit ramping down limit:

$$PG_{(k-1)g} - PG_{kg} \le [1 - W_{(k-1)g}(1 - W_{kg})]RD_g + W_{(k-1)g}(1 - W_{kg})P\min_g$$
$$g = 1,...,NG; k = 1,...,NK \quad (18)$$

Unit minimum ON time limit:

$$[X^{on}_{(k-1)g} - T^{on}_g](W_{(k-1)g} - W_{kg}) \ge 0$$
$$g = 1,...,NG; k = 1,...,NK \quad (19)$$

Unit minimum OFF time limit:

$$[X^{off}_{(k-1)g} - T^{off}_g](W_{kg} - W_{(k-1)g}) \ge 0$$
$$g = 1,...,NG; k = 1,...,NK \quad (20)$$

Unit generation limit:

$$P\min_g * W_{kg} \le PG_{kg} \le P\max_g * W_{kg}$$
$$g = 1,...,NG; k = 1,...,NK \quad (21)$$

Network constraint:

$$PG_{kg} + pwind_{kg} - Pdf_{ki} - Pdr_{ki} = \sum_{j=1}^{NI} pline_{kij} \quad (22)$$
$$pline_{kij} = Bline_{ij} * (delta_{ki} - delta_{kj}) \quad (23)$$
$$pline_{kij} \le pl\max_{kij} \quad (24)$$

The scenario constraints (25)–(36) represent the system power balance (25), system spinning reserve (26) and (27), system operating reserve (28) and (29), permissible adjustment of real power generation (30), unit generation (31), network constraints (31) –(34), and responsive load constraints (35) and (36).

$$\sum_{g=1}^{NG} PG^s_{kg} * W_{kg} = \sum_{i=1}^{NI} Pdnet^s_{ki} + Pdr^s_{ki}$$
$$Pdnet^s_{ki} = Pdf^s_{ki} - Pwind^s_{ki}$$
$$k = 1,...,NK \quad (25)$$

$$\sum_{g=1}^{NG} PSR^s_{kg} * W_{kg} \ge SR_k$$
$$k = 1,...,NK \quad (26)$$

$$PSR^s_{kg} \le 10 * MSR_{kg} * W_{kg} \quad (27)$$

$$\sum_{g=1}^{NG} PNSR^s_{kg} * W_{kg} \ge NSR_k$$
$$k = 1,...,NK \quad (28)$$

$$PNSR^s_{kg} \le QSC_{kg} \quad (29)$$

$$\left| PG^s_{kg} - PG_{kg} \right| \le \Delta_g$$
$$g = 1,...,NG; k = 1,...,NK \quad (30)$$

$$P\min_g * W_{kg} \le PG^s_{kg} \le P\max_g * W_{kg}$$
$$g = 1,...,NG; k = 1,...,NK \quad (31)$$

$$PG^s_{kg} - Pdnet^s_{ki} - Pdr^s_{ki} = \sum_{j=1}^{NI} pline^s_{kij} \quad (32)$$

$$pline^s_{kij} = Bline_{ij} * (delta^s_{ki} - delta^s_{kj}) \quad (33)$$

$$pline^s_{kij} \le pl\max_{kij} \quad (34)$$

$$Pdr^s_{ki} \le (Pdr\max_{ki} - Pdx\ \min_{ki}) * M_{ki} + Pdr\max_{ki} * (1 - M_{ki}) \quad (35)$$

$$Pdr^s_{ki} \ge Pdr\max_{ki} * (1 - M_{ki}) \quad (36)$$

D. Proposed Method

Table 1 shows the proposed method algorithm.

TABLE 1. ALGORITHM OF PROPOSED METHOD USING BENDERS DECOMPOSITION

	Solving Problem Algorithm
1	Solve Master Problem (Conventional UC Problem With DR and Wind generation)
2	If Threshold > **ε**
3	Solve Sub-problem for different Wind generation scenarios
4	Calculate feasibility Cost at each hour for each
5	Create Feasibility Cost Cut and add to Master problem
6	Repeat this procedure until Threshold < **ε**
7	Print the UC and DR result

First of all, the optimization problem will be run using (3). The results of this optimization should be checked for different wind generation and load scenarios. Therefore, the results will be conducted to the next optimization problem which is called sub-problem. In this part, the assigned UC, PSR, NSR and DR program will be checked in presence of different wind generation and load scenarios. Based on Benders decomposition approach, if one or more constraints being violated during optimization, the Benders cut associated with the bus and the time which constraint is violated will be created and added to the master problem. Technically, this cut will add feasibility cost to the original objective function. The procedure will be repeated until the feasibility cost (threshold) being less than feasibility minimum rate **ε**.

III. Numerical Studies

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In this section, the results of applying proposed method on IEEE six-bus test system is discussed. The data for this system are given in [13]. Three responsive loads are located in the system and will participate in DR program. In addition the wind farm is connected to the Bus 4 and provide power for system. Twenty percent of the total load in these buses are considered as responsive while the rest is fixed. Characteristics of responsive loads are presented in Table 2.

In order to show the importance of DR program and its role to increase the system efficiency, the results are discusses in two part. In the first part, SCUC is done when the wind farm provided to the system but DR program is not considered. In the next part, SCUS is done when both DR program and wind power generation are considered and utilized in the system. GAMS software (CPLEX solver) is employed to solve the problem [14].

Table 2. CHARACTERISTICS OF RESPONSIVE LOADS

Bus No.	B ($/MWh)	MUT (h)	MDT (h)	RampUp (MW/h)	RampDn(MW/h)
3	27	2	1	20	30
4	25	3	2	30	35
5	22	2	1	40	50

A. SCUC Without DR program

In this case, we assume that the load is fixed (DR is not considered) in SCUC. The results of UC are shown in Table 3. System operation cost for 24 hour would be 135721.083$.

B. SCUC with DR Program

In this part, the results of the optimization considering both demand response and wind generation are discussed. Table 4 shows the SCUC results and generation unit status for next 24 hour. One can find that generation unit 1 is the most economical generator in the system and so this unit will provide power for system most of the time. On the other hand, Generation unit 3 is the most expensive unit in the system so this unit mostly provide non-spinning reserve for the system .The operation cost for this optimization is $ 116136.236 which has decreased by %14.4 compares to previous case. Figure 1 compares system load prolife of 2 case studies. As it can be seen, peak demand is reduced by either curtailing responsive loads or shifting responsive loads to off-peak hours. This peak load reduction would alleviate price spikes and enhance flexibility and efficiency of market operations.

IV. Conclusion

In this paper, a SCUC algorithm was proposed to model DR in clearing of electricity market based on stochastic wind power generation. Physical constraints of responsive loads together with generating units and transmission lines were considered in base case and different wind generation and load scenarios. The problem is formulated as an MIP problem and solved using Benders decomposition. The results of simulation on the IEEE six-bus test system are:

- The proposed method offers a flat load and LMP profiles.
- The method leads to lower system operation costs and higher market efficiency
- providing a robust unit commitment by taking into account the intermittency and volatility of wind power generation as well as reducing ON/OFF commitment of generating units.

Suggestions for future research resulting from the proposed model are listed below:

1- Demand response resources are technically capable of providing operating reserve, which can be formulated in the proposed method with few changes.

2- The proposed model can also be extended to stochastic day-ahead scheduling with plug-in vehicles in which uncertainties associated with renewable energy are considered.

Table 3. Generation dispatch without DR

Hour	PG1	U1	PG2	U2	PG3	U3	WF
1	200.0	0.0	0.0	0.0	35.6	0.0	44.0
2	186.4	0.0	0.0	0.0	15.6	0.0	70.2
3	200.0	0.0	10.3	1.0	0.0	0.0	76.0
4	190.9	0.0	10.0	0.0	0.0	0.0	82.0
5	179.5	0.0	10.0	0.0	0.0	0.0	84.0
6	184.9	0.0	0.0	0.0	0.0	0.0	84.0
7	183.4	0.0	0.0	0.0	0.0	0.0	100.0
8	187.6	0.0	0.0	0.0	0.0	0.0	100.0
9	197.3	1.0	19.4	1.0	0.0	0.0	78.0
10	200.0	0.0	49.4	0.0	0.0	0.0	64.0
11	200.0	0.0	38.0	0.0	0.0	0.0	100.0
12	200.0	0.0	53.3	0.0	0.0	0.0	92.0
13	200.0	0.0	66.6	0.0	0.0	0.0	84.0
14	200.0	0.0	61.0	0.0	10.0	1.0	80.0
15	198.8	0.0	69.9	0.0	10.0	0.0	78.0
16	197.1	0.0	99.9	0.0	30.0	0.0	32.0
17	182.9	0.0	128.3	0.0	41.2	0.0	4.0
18	188.4	0.0	118.0	0.0	33.1	0.0	8.0
19	189.7	0.0	115.6	0.0	31.7	0.0	10.0
20	190.5	0.0	114.1	0.0	28.3	0.0	5.0
21	192.8	0.0	99.1	0.0	40.0	0.0	6.0
22	198.2	0.0	64.1	0.0	20.0	0.0	56.0
23	193.0	0.0	29.1	0.0	0.0	0.0	82.0
24	200.0	0.0	47.0	0.0	0.0	0.0	54.0

Table 4. Generation dispatch considering DR

Hour	PG1	U1	PG2	U2	PG3	U3	WF
1	200.0	0.0	0.0	0.0	20.0	0.0	44.0
2	197.5	0.0	0.0	0.0	0.0	0.0	70.2
3	197.6	0.0	0.0	0.0	0.0	0.0	76.0
4	197.7	0.0	0.0	0.0	0.0	0.0	82.0
5	197.7	0.0	0.0	0.0	0.0	0.0	84.0
6	197.6	0.0	0.0	0.0	0.0	0.0	84.0
7	197.4	0.0	0.0	0.0	0.0	0.0	100.0
8	197.2	0.0	0.0	0.0	0.0	0.0	100.0
9	200.0	0.0	28.1	1.0	0.0	0.0	78.0
10	200.0	0.0	58.1	0.0	0.0	0.0	64.0
11	200.0	0.0	51.8	0.0	0.0	0.0	100.0
12	200.0	0.0	59.7	0.0	0.0	0.0	92.0
13	200.0	0.0	57.1	0.0	0.0	0.0	84.0
14	200.0	0.0	57.3	0.0	0.0	0.0	80.0
15	200.0	0.0	60.4	0.0	0.0	0.0	78.0
16	200.0	0.0	86.5	0.0	20.0	1.0	32.0
17	196.0	0.0	103.8	0.0	38.4	0.0	4.0
18	200.0	0.0	96.4	0.0	31.5	0.0	8.0
19	200.0	0.0	96.4	0.0	31.2	0.0	10.0
20	200.0	0.0	96.4	0.0	28.4	0.0	5.0
21	200.0	0.0	93.1	0.0	20.0	0.0	6.0
22	200.0	0.0	65.8	0.0	0.0	0.0	56.0
23	200.0	0.0	34.0	0.0	0.0	0.0	82.0
24	200.0	0.0	58.8	0.0	0.0	0.0	54.0

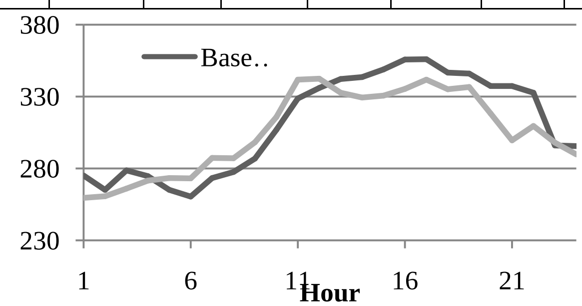

Figure 1. Comparison between load profile (MW) while there is no DR and DR is utilized.

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