Stochastic Security-Constrained Unit Commitment with ARMA-based Wind Modelling Considering Network Uncertainties

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Abstract- This paper proposes a short-term stochastic SCUC model that simultaneously schedules generating units' energy and spinning reserve in presence of wind energy. It should be noted that system uncertainties, wind farm output uncertainties and power generators and lines outages are also considered in optimization process. The proposed stochastic SCUC model is formulated as a two-stage stochastic mixed-integer programming model. Performance of the proposed formulation is proved through test systems and the results are also presented.

Keywords- Security Constraint Unit Commitment (SCUC), Monte Carlo, Wind Farm, Auto-Regressive Moving Average (ARMA), Stochastic

1. Introduction

The Generation scheduling (short-tem/long-term), which is known as unit commitment (UC) program, is an important challenge in power systems. It is necessary to design an algorithm to solve this problem. Multiple algorithms have been proposed to solve this kind of problems which can be categorized in three groups: numerical methods, intelligent methods and combinational methods. Intelligent methods do not provide good numerical convergence and accurate answers [1] Methods like priority list, dynamic programming, branch and bound method, Lagrange method and integer number programming can increase accuracy of the final answer [2,3]. In restructured environments, ISO uses security constraint unit commitment (SCUC) to program for the next day [4] The constraints that should be considered in this program include: network generation constraint, minimum and maximum production of each unit, minimum and maximum online/offline duration of each unit, spinning reserve, Ramp-up and ramp-down limit of each unit and also the network constraints like power transmission limit of each line and bus voltages [5]. The larger the network size, the more the parameters. Size of the network determines number of the parameters. Effects of wind farm on SCUC program studies in [6-7]. In [9-10] load forecasting is done using calculative methods and results are used in economic dispatch (ED) and UC problems. An algorithm is proposed in [11] for (UC) with security constraints. A methodology to determine amount of spinning and non-spinning reserves in presence of wind units is presented in [12]. The rest of this paper is organized as follows. Monte Carlo approach and modeling of the network uncertainties is explained in Section 3, Section 4 formulates this model as a large-scale mixed integer linear programming (MILP) problem. In Section 5 case studies are presented and discussed. Section 6 provides some relevant conclusions.

2. Monte Carlo Approach and Modelling of the Network Uncertainties

Monte-Carlo is the best method for simulation of stochastic behavior of power system equipment. This method is used in this paper for simulation of normal state, units and transmission lines outages.

2.1. Load Forecast Uncertainties

In this paper normal distribution is used to model the load forecast uncertainties.

The mean of the normal distribution describes the peak load forecast. To model the load forecast error, the normal distribution with 5 intervals is employed in the simulation process on the case studies. The statistical distribution is divided into 5 intervals Lower limit of first interval is zero, and upper limit of the last interval is one. Lower limit of each interval is cumulative probability of previous one and upper limit is cumulative probability of the current span. Figure 1 shows the five part normal distribution.

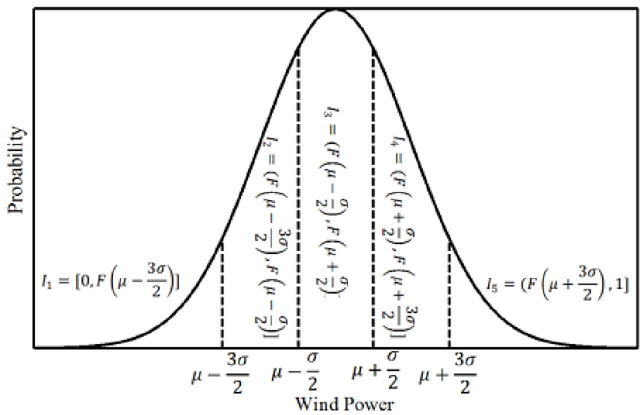

Fig. 1. Normal distribution with five intervals

2.2. Wind Farm Modelling

Wind speed varies with time and location and is related to the wind speeds of the previous hours. Considering uncertainties and the stochastic nature of wind speed an auto-regressive moving average (ARMA) time series method is used modelling wind speed. Here is a brief review to simulate wind speed by ARMA time series method:

1- Create random white noise α_t

2- Calculate y_t from random white noise and previous values of y_t

3- Calculate wind speed using step 1.

4- Steps 1, 2 and 3 are repeated for the entire time interval.

$$y_t = 0.8782 y_{(t-1)} - 0.0066 y_{(t-2)} + 0.0265 y_{(t-3)} + \alpha_t - 0.2162 \alpha_{(t-1)} - 0.0091 \alpha_{(t-2)} \quad (1)$$

$$\alpha_t \in NID\left(0, 0.55792^2\right)$$

y_t is the time series value at time t and α_t is a normal white noise process with zero mean and variance of $\sigma_t^{\,2}$. WS_t is the hourly simulated wind speed can be calculated from (2) Where μ_t is the mean speed and σ_t its standard deviation.

$$WS_t = \mu_t + \sigma_t y_t \quad (2)$$

The relationship between power output and wind speed can be presented by using operational parameters of the wind turbine (3). These parameters are cut-in, cut-out and rated wind speeds.

$$P_t^w = \begin{cases} 0 & , \quad 0 \le SW_t < V_{ci} \\ \left(A + B \times SW_t + C \times SW_t^2\right) \times P_r & , \quad V_{ci} \le SW_t < V_r \\ P_r & , \quad V_r \le SW_t < V_{co} \\ 0 & , \quad SW_t \ge V_{co} \end{cases} \quad (3)$$

And

$$A = \frac{1}{\left(V_{ci} - V_r\right)^2}\left\{V_{ci}\left(V_{ci} + V_r\right) - 4 V_{ci} V_r \left[\frac{V_{ci} + V_r}{2V_r}\right]^3\right\} \quad (4)$$

$$B = \frac{1}{\left(V_{ci} - V_r\right)^2}\left\{4\left(V_{ci} + V_r\right)\left[\frac{V_{ci} + V_r}{2V_r}\right]^3 - \left(3V_{ci} + V_r\right)\right\} \quad (5)$$

$$C = \frac{1}{\left(V_{ci} - V_r\right)^2}\left\{2 - 4\left[\frac{V_{ci} + V_r}{2V_r}\right]^3\right\} \quad (6)$$

Where V_r ,V_{ci} ,P_r and V_{co} are the rated power output, the cut-in wind speed, the rated wind speed, and the cut-out wind speed of the wind turbine.

All the wind turbine used in this study are assumed to have a rated capacity of 1 MW and cut-in, rated, and cut-out speeds of 3, 25 and 12 m/s, respectively. Based on ARMA, 200 scenarios was generated modeling wind speed and (3) is used to obtain wind power output from wind speed. Data for wind farm site can be seen in Table 1.

Table 1. Wind site specification for 6 bus system

Wind bus	Wind farm mean speed (km/h)	Standard deviation (km/h)
Bus 4	17/230	10/560

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2.3. Scenario Reduction

In the initial, probability of each scenario is same. To reduce the number of possible scenarios a compromise between the solution accuracy and computation speed should be done since based on the number of scenarios the computation speed changes. Regarding the solution accuracy the following criterion for the scenario reduction has been used:

$$cv_x = \frac{\sigma_x}{\mu_x \sqrt{N_s}} \le 0.2.5\% \tag{7}$$

Where:

cv_x : Stop criteria

σ_x : Covariance of scenarios

μ_x : Average of scenarios

Ns: Number of scenarios

2.4. Scenario Aggregation

Two-stage stochastic programming method is an appropriate scenario method which is used in this paper. In the first stage network constrained UC in the base case with considering any scenarios are dealt with. The second-stage surveys security issues in system scenarios and we are employing all available resources to supply load in each scenarios. The second-stage of the two-stage model indicates cost of providing security in system scenarios.

3. Formulation

The objective function to be minimized is the total cost (TC):

$$TC=\sum_{t=1}^{N_t}\Bigg\{\sum_{i=1}^{N_g}\left(MC_iU_{it}+\sum_{seg=1}^{N_{seg}}R_{it}^{seg}P_{it}^{seg}+SU_{i,t}+SD_{i,t}\right) + \sum_{i=1}^{N_g}\left(RC_i^{uc}SR_{it}^{u}+RC_i^{dc}SR_{it}^{d}\right) + \sum_{s=1}^{N_S} prob_S SC_S \Bigg\} \tag{8}$$

$$SC_S=\sum_{i=1}^{N_g}\left(RC_i^{ue}sr_{it}^{u}+RC_i^{de}sr_{it}^{d}\right)+\sum_{d=1}^{N_d}VOLL_{dt}LS_{dts} \tag{9}$$

To avoid nonlinearity in the optimization problem, a piecewise linear cost function is used in this paper so the cost function of thermal units which is a function of order 2 is considered linear here.

$$\begin{aligned} &P_{it}=P_i^{min}U_{it}+\sum_{seg=1}^{N_{seg}}P_{it}^{seg} \quad \forall i,t \\ &0\le P_{it}^{seg}\le P_{it}^{seg,max} \quad \forall i,t \end{aligned} \tag{10}$$

The first-stage constraints are associated with the base case, including the following:

-Minimum and maximum output power :

$$\begin{aligned} &P_{it}+SR_{it}^{u}\le P_i^{\max} \quad \forall i,t \\ &P_{it}-SR_{it}^{d}\ge P_i^{\min} \quad \forall i,t \end{aligned} \tag{11}$$

- Ramping up and Ramp down constraints:

$$\begin{aligned} &P_{i,t}-P_{i,t-1}\le[1-U_{i,t}.(1-U_{i,t-1})]RU_i \\ &\quad +U_{i,t}(1-U_{i,t-1})P_i^{\min} \quad \forall i,t \\ &P_{i,t-1}-P_{i,t}\le[1-U_{i,t-1}.(1-U_{i,t})]RD_i \\ &\quad +U_{i,t-1}(1-U_{i,t})P_i^{\min} \quad \forall i,t \end{aligned} \tag{12}$$

-Minimum on/off time of each unit:

$$\begin{aligned} &(\textstyle\sum_{ON}U_{i,t}-T_{on\ i}^{\min}).(U_{i,t-1}-U_{i,t})\ge 0 \quad \forall i,t \\ &(\textstyle\sum_{OFF}U_{i,t}-T_{off\ i}^{\min}).(U_{i,t}-U_{i,t-1})\ge 0 \end{aligned} \tag{13}$$

-Upper limits of various types of reserves:

$$\begin{aligned} &0\le SR_{it}^{u}\le\tau\times RU_i \quad \forall i,t \\ &0\le SR_{it}^{d}\le\tau\times RD_i \quad \forall i,t \end{aligned} \tag{14}$$

-DC power flow equation in steady state

$$\begin{aligned} &\sum_{i=1}^{N_g}P_{it}+\sum_{k=1}^{w}Pw_{kt}-\sum_{d=1}^{N_d}P_{dt}=\sum_{\ell=1}^{N_\ell}f_\ell \quad \forall i,t \\ &f_\ell=\frac{1}{X_l}(\delta_s-\delta_\ell) \\ &-F_\ell^{\max}\le f_\ell\le F_\ell^{\max} \quad \forall i,t \end{aligned} \tag{15}$$

The second-stage constraints which are considered in system Scenarios are as follows:

-DC power flow equation in scenarios:

$$\begin{aligned} &\sum_{i=1}^{N_g}\varepsilon_{Gi}^{s}P_{it}+\sum_{i=1}^{N_g}\varepsilon_{Gi}^{s}sr_{its}^{u}-\sum_{i=1}^{N_g}\varepsilon_{Gi}^{s}sr_{its}^{u}+ \\ &\qquad \sum_{d=1}^{N_d}LS_{dts}+\sum_{k=1}^{w}Pw_{kts}=\sum_{\ell=1}^{N_\ell}f_{\ell s} \end{aligned} \tag{16}$$

$$f_{\ell s}=\varepsilon_{\ell}^{s}\left[\frac{1}{X_{l}}(\delta_{\$}^{s}-\delta_{\ell}^{s})\right] \tag{17}$$

$$-F_{\ell}^{\max}\leq f_{\ell s}\leq F_{\ell}^{\max}\quad\forall\ell t,s \tag{18}$$

As can be seen in the above equations parameters ε_{Gi}^{s} and ε_{ℓ}^{s} respectively shows availability of thermal units and transmission lines.

-up and down-spinning reserve limit:

$$\begin{aligned}0\leq sr_{its}^{u}&\leq\varepsilon_{Gi}^{s}SR_{it}^{u}\\0\leq sr_{its}^{d}&\leq\varepsilon_{Gi}^{s}SR_{it}^{d}\end{aligned} \tag{19}$$

-Load shedding limit:

Maximum load shedding is total load on each bus and cost of loss of load is considered 1000 $/Mwh.

4. Case Study

Case 1:

The first case study is a 6 bus IEEE network like [12]. All the constraints introduced in previous sections are considered. CPLEX method is used in GAMS environment for optimization.

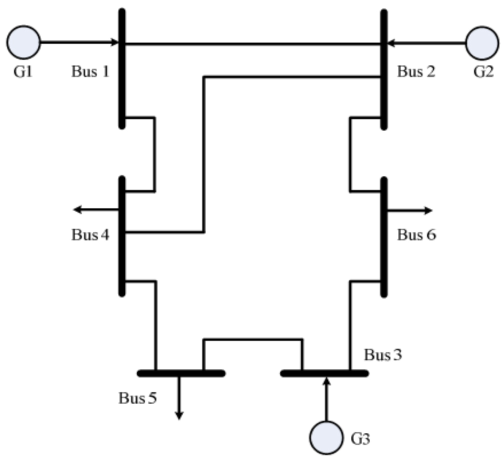

Fig. 2. 6 bus IEEE network

The six-bus system shown in Figure 2 is used to demonstrate the features of the proposed model. Failure rate and mean down time of generating units and transmission lines are presented in [13]. Here at first 200 scenarios are generated deploying scenario reduction with the GAMS/SENRED program, 12 scenarios remained. Table 2 shows the probability of remained scenarios.

Table 2. The probability of remained scenarios

S	1	2	3	4	5	6
P	0/002	0/12	0/01	0/1	0/004	0/004
S	7	8	9	10	11	12
P	0/004	0/004	0/104	0/004	0/024	0/62

S=scenario number P: probability

Assume that the wind farm with capacity of 100 Mw is connected to bus 4 in a 6 bus IEEE network.

4.1. Wind Penetration

Wind farm penetration percentage (WFPP) means contribution of the wind farm in total generated power to the network. (20) Shows the formulation that calculates percentage of penetration, where $P_{non-wind}$ is total output power of non-wind units. Figure 3 shows the penetration for IEEE 6 bus.

$$\text{WFPP}=\frac{P_{wind}}{P_{wind}+P_{non-wind}}\times 100 \tag{20}$$

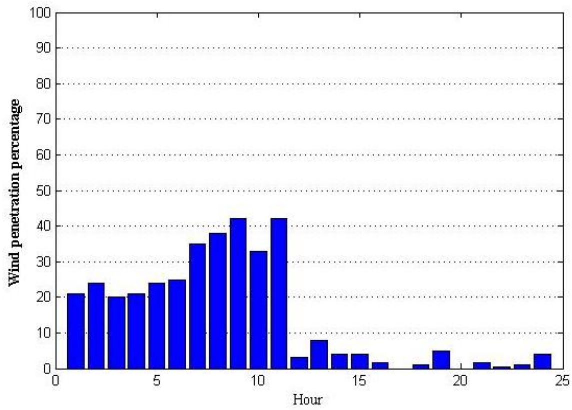

Fig. 3. Wind farm penetration percentage

Wind penetration changes throw hours and sometimes it's equal to zero due to variation in of wind speed. No cost has been considered for wind farm operation, connecting the wind unit to the network reduces the total operation cost. The total operation cost (OC) for IEEE 6 bus in presence of wind unit is shown in Table 3, Table 4 shows total cost without considering wind generation (137373.690$) which is higher.

Table 3. Costs and non-supplied energy considering wind farm

Total cost ($)	OC ($)	Energy not supplied (MW)
119499.047	93353.2	26.14

Table 4. Costs and non-supplied energy without wind

Total cost ($)	OC ($)	Energy not supplied (MW)
137373.81	101088.34	36.28

Case 2:

It should be noted that due to large oscillations in wind unit outputs which for some hours is near zero, thermal units need to be adjusted to this changes but regarding to constraints like ramp up & ramp down and also min up time and min down time this immediate changes in thermal units outputs gets impossible. As shown in IEEE 6 bus structure , bus 4 which is connected to wind farm has a direct line to bus 1 so thermal unit in bus 1 has been used less therefore Bus 2 and 3 due to line flow limitation, congestion and less production of unit 1 operate at higher generation level and use more fuel . To demonstrate the effect of wind generation and wind output oscillations on network , we reduced the maximum generation for unit 3 from 100 MW to 60 MW, the wind unit like before is placed on bus 4, this change makes the total cost 169610.350$ which is larger than previous as expected. It's obvious that decreases in unit 3 output should compensate by other units, but here we have no change in unit one output since unit 2 generation grows 70%, it's because of constraints like ramp up & down and also min up time and min down time besides transmissions line limitations so the loss of load in the system increases and this will reduce system reliability however operation cost is lower than the case without wind farm but total cost increases (Table 5), but wind bus (bus 4) has a direct line to bus 1 therefore no changes happened in unit 1 production (Figure 4).

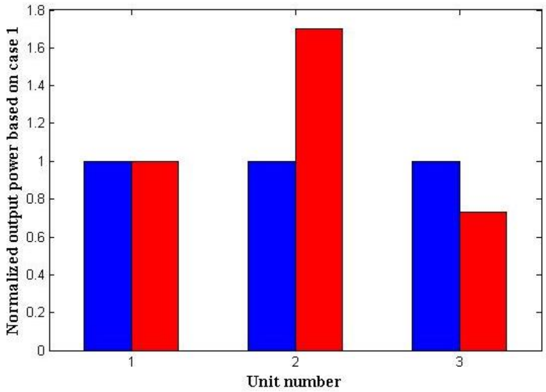

Fig. 4. Normalized output power of thermal units based on case 1

Table 5. Costs and non-supplied energy of case 2

Total cost ($)	OC ($)	Energy not supplied (MW)
169610.357	94668	74.94

Case 3:

The case study here is a 24 bus IEEE network as [14]. Assume the wind farm with capacity of 100 Mw is connected to bus 4. The total operation cost for IEEE 24 bus in presence of wind unit is 696334.45 $ which is lower than cost without considering wind generation (719686.640$). The loss of load probability for IEEE 24 bus reduces from 0.11 to .063 in presence of wind unit. Figure 5 and Figure 6 show load shedding for scenario number 3, as expected wind unit decreases the amount of involuntary load curtailments.

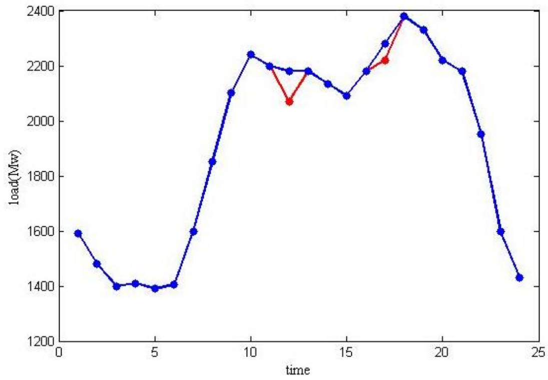

Fig. 5. Load shedding in scenario 3 for IEEE 24 bus considering wind generation

Program run time for this case study is about 5 min in GAMS 23.6 environment on a DELL vostro computer with a 2.2GHz core2duo processor and 2 GB of RAM.

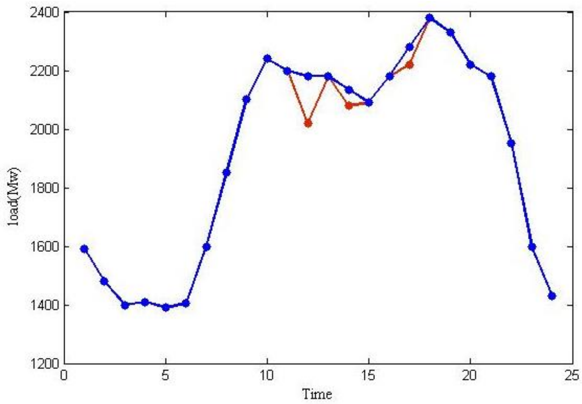

Fig. 6. Load shedding in scenario 3 for IEEE 24 bus without wind generation

5. Conclusion

In this paper the efficiency of Monte Carlo approach to stochastic programming in the network uncertainties management and integration of wind generation to the network was illustrated. With stochastic programming based on scenario generation it's possible to consider system components outages without increasing Calculations besides scenario reduction method chooses high risk scenarios and scenarios with high probability. Wind farm Integration to the network decreases total system operation cost and network energy not supplied due to insignificant operation cost of wind units also decreases in network energy not supplied increases system reliability. It should be noted if wind farm is connected to the grid instead of other thermal unit (case 2) due to large oscillations in wind unit outputs which for some hours is near zero, thermal units need to be adjusted to this changes but regarding to constraints like ramp up & ramp down and also min up time and min down time this immediate changes in thermal units outputs gets impossible so the loss of load in the system increases and this will reduce system reliability however operation cost is lower than the case without wind farm but total cost increases.

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