Maintenance Scheduling of Integrated Electric and Natural Gas Grids with Wind Energy Integration

Chong Wang, Zhaoyu Wang, Kai Zhou, Shanshan Ma
Department of Electrical and Computer Engineering
Ames, IA, USA
wangc@iastate.edu, wzy@iastate.edu, kzhou@iastate.edu, sma@iastate.edu

***Abstract*— With the growing interaction between natural gas grids and electric power grids associated with the high integration of large-scale wind generation, this paper establishes short-term maintenance strategies for integrated natural gas and electric grids with wind energy integration. Scenarios are simulated to represent wind power volatility. To overcome the adversities caused by the nonlinear and non-convex models of natural gas systems, a piecewise linear approximation approach is used to transform the original nonlinear models into mixed integer linear models. To ensure power balance and gas balance for transmission lines and gas pipelines, a big-M formulation method is used to construct inequalities constraints. The entire problem is modeled as a mixed integer linear programming problem. Numerical tests on a 6-bus system with a 4-node gas gird show the effectiveness of the proposed model.**

***Index Terms*— maintenance scheduling, natural gas grid, security-constrained, stochastic, wind power**

NOMENCLATURE

Indices and Sets

gu	Index of generating units
wf	Index of wind farms
gw	Index of gas wells
gs	Index of gas storages
gn, gn'	Index of gas nodes
pn, pn'	Index of power nodes
l	Index of transmission lines to be maintained
l'	Index of transmission lines not to be maintained
p	Index of pipelines to be maintained
p'	Index of pipelines not to be maintained
pc	Index of pipelines with compressors
s	Index of wind power generation scenarios
t, t'	Index of time periods
Φ_{pn}^{GU}	Set of generating units at power node pn
Φ_{pn}^{WF}	Set of wind farms at power node pn
Φ_{pn}^{PD}	Set of power loads at power node pn
Φ_{pn}^{PN}	Set of power nodes connected with node pn
Φ_{gn}^{GW}	Set of gas wells at gas node gn
Φ_{gn}^{GS}	Set of gas storages at gas node gn
Φ_{gn}^{GF}	Set of gas-fired units at gas node gn
Φ_{gn}^{GD}	Set of normal gas loads at gas node gn
Φ_{gn}^{GN}	Set of gas nodes connected with gas node gn
Φ_{CP}	Set of pipelines with compressors

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Parameters

$B_{pn,pn'}$	Electrical susceptance of line $pn-pn'$
$C_{l,t}^{M}, C_{p,t}^{M}$	Maintenance costs of line l and pipeline p at t
$C_{gu,t}^{F}, C_{gu,t}^{L}$	Fixed cost and linear cost of generator gu at t
$C_{gu,t}^{S}$	Start-up cost of generator gu at t
$C_{gw,t}, C_{gs,t}$	Cost of gas production and storage at t
$C_{pn,t}^{LS}$	Cost of load shedding of node pn at t
$C_{gn,gn'}$	Weymouth constant of pipeline $gn-gn'$
EF_{gu}	Efficiency factor of gas-fired unit gu
$\bar{G}_{gw}, \underline{G}_{gw}$	Max and min outputs of gas well gw
$\bar{S}_{gs}, \underline{S}_{gs}$	Max and min outputs of gas storage gs
$L_{gn,t}$	Gas Loads of gas node gn at t (non-gas-fired unit)
$L_{pn,t}$	Power load demand of node pn at t
M_l, M_p	Large numbers
N_{PN}, N_{GN}	Number of power nodes and gas nodes
N_{GU}, N_{GW}	Number of generating units and gas wells
N_L, N_P	Number of all transmission lines and pipelines
N_{GS}, N_{WF}	Number of gas storages and wind farms
N_{ML}	Number of transmission lines to be maintained
N_{MP}	Number of pipelines to be maintained
N_S	Number of wind power generation scenarios
$\bar{N}_t^{L,M}, \bar{N}_t^{P,M}$	Max number of lines and pipelines under maintenance at t
$\bar{P}_{gu}, \underline{P}_{gu}$	Max and min outputs of generator gu
$\bar{P}_{pn,pn'}^{L}$	Max capacity of line $pn-pn'$
$\underline{P}_{pn,pn'}^{L}$	Min capacity of line $pn-pn'$

$P_{wf,t,s}$	Wind power of wind farm *wf* at *t* under scenario *s*
$\overline{R}_{gu}, \underline{R}_{gu}$	Ramp-up and ramp-down limits of generator *gu*
$\overline{R}_{gs}, \underline{R}_{gs}$	In-flow and out-flow limits of gas storage *gs*
$\underline{\theta}_{pn}, \overline{\theta}_{pn}$	Min/max of phase angles of node *pn*
$\underline{\pi}_{gn}, \overline{\pi}_{gn}$	Min/max squared pressures
λ_{pc}	Compression factor
$\mu_{wf,t}$	Forecast power of wind farm *wf* at *t*
$\sigma^2_{wf,t}$	Deviation of wind power at wind farm *wf* at *t*

Variables

$F_{gn,gn',t,s}$	Gas flow from *gn* to gn' at *t* under scenario *s*
$G_{gw,t}$	Gas production of gas well *gw* at *t*
$S_{gs,t}, S_{gs,t-1}$	Gas inventory of gas storage *gs* at *t* and *t*-1
$L_{gu,t}$	Gas consumption of gas-fired unit *gu* at *t*
$\Delta L_{gn,t,s}$	Gas load shedding of gas node *gn* at *t* under scenario s (non-gas-fired unit)
$\Delta L_{pn,t,s}$	Load shedding of node *pn* at *t* under scenario *s*
$m_{l,t}$	Binary variable to indicate if transmission line *l* is under maintenance at *t*. '1' denotes maintenance, otherwise '0'
$P_{gu,t}$	Power generation of generator *gu* at *t*
$P^L_{pn,pn',t,s}$	Power from node *pn* to pn' at *t* under scenario *s*
$PS_{gn,t,s}$	Pressure of gas nodes *gn* at *t* under scenario *s*
$\theta_{pn,t,s}, \theta_{pn',t,s}$	Phase angles of nodes at *t* under scenario *s*
$\pi_{gn,t,s}, \pi_{gn',t,s}$	Squared pressures of gas nodes *gn* and gn'

I. Introduction

To use green electricity, increasing wind farms and natural gas-fired units are integrated into the conventional power systems. The operating characteristics of natural gas grids and the uncertain wind power generation have brought challenges into the operation of conventional power grids. Power system maintenance scheduling, as an important means to keep high component reliability, is influenced by the integration of wind power and natural gas grids. Particularly, natural gas grids also need maintenance to ensure their high reliability. Therefore, it is imperative to analyze the maintenance scheduling of integrated natural gas grids and power grids with wind energy.

Because of the linkage between natural gas grids and power grids, the influences of natural gas grids on the conventional power systems should be included. For example, outages of gas-fired units, due to gas pressure losses and pipeline contingencies, may increase the operating costs and jeopardize the power system security [1]. To include the influences of gas grids on power system operation, [2] presents a security-constrained unit commitment with natural gas transmission constraints, which are expressed as a set of nonlinear equations. In addition, many models, e.g., Markov models and mixed integer linear programming (MILP) models, have been proposed to establish maintenance scheduling. To include uncertainties of deterioration processes of devices, a Markov model is introduced to represent deterioration processes to establish optimal maintenance policies [3]. Considering the influences of external harsh weather events, a probabilistic model is proposed to establish maintenance strategies in [4]-[6]. A backward induction [7] with a search space reduction method is employed to improve computational efficiency while still maintaining a good accuracy. [8] discusses the properties of Markov processes and analyzes whether these properties are realistic. In addition to Markov models, some models [9] [10] are proposed to schedule maintenance activities on electric devices by using MILP. To solve these MILP models, many approaches, e.g., the Benders decomposition method [11] [12], are employed. The above studies are under the environment of a centralized power system. With the deregulation of power systems, centralized maintenance scheduling is not suitable. In [13], an iterative procedure, coordinating generation maintenance scheduling between an independent system operator and generation companies, is proposed to achieve an acceptable system reliability. In [14], a bi-level model is proposed to establish the yearly maintenance scheduling of generators in a deregulation environment. In [15], a coordination mechanism for generation maintenance scheduling in market environments is proposed. A relaxation reduction algorithm is utilized to solve the proposed large mixed integer programming problem.

Though the topics of maintenance scheduling and integrated natural gas and power grids have been well studied, there is few work investigating maintenance scheduling of integrated natural gas and power grids particularly with wind energy. The contribution of this paper is to propose a stochastic security-constrained model to establish short-term maintenance scheduling for integrated natural gas and electric grids with wind energy. The remainder of this paper is organized as follows. Section II shows the maintenance scheduling formulation, including the model of wind power generation, the model of natural gas grids, the model of power grids, and the stochastic security-constrained model. Section III presents the case studies, and the work is concluded in Section IV.

II. Maintenance Scheduling Formulation

This section presents the model of security-constrained maintenance scheduling of electric and natural gas grids with wind energy.

A. Wind Power Generation

Currently, there are two common approaches to represent uncertainties of wind power generation. The first one is the scenario-based approach, which generates limited scenarios to approximate the distribution of wind power [16]. The second one is the uncertainty set approach, which employs a set of inequalities, including the upper/lower bounds of uncertainties and the intensity of power fluctuations, to characterize the uncertainty of wind power [17].

Many probability distributions, e.g., normal distributions and Weibull distributions, have been developed to forecast wind power generation. With these distributions, the Monte Carlo simulation (MCS) can be used to generate wind power scenarios at each time period. Each scenario s has a probability $1/N_S$. Since the MCS method needs a large number of scenarios to get a reasonably accurate random distribution, the Latin hypercube sampling (LHS) technique is used to achieve a satisfied accuracy with reduced scenarios.

B. Natural Gas (NG) Grid

1) Operating constraints of natural gas grids

NG production: Gas production of each gas well is limited by maximum and minimum values.

$$\underline{G}_{gw} \le G_{gw,t} \le \bar{G}_{gw} \qquad \forall gw,t \tag{1}$$

NG storages: The maximum storage level should satisfy the constraint

$$\underline{S}_{gs} \le S_{gs,t} \le \bar{S}_{gs} \quad \forall gs,t \tag{2}$$

In addition, the in-flow and out-flow rates of storages should be within the limits.

$$\underline{R}_{gs} \le S_{gs,t} - S_{gs,t+1} \le \bar{R}_{gs} \quad \forall gs,t \tag{3}$$

NG balance at each gas node: For each wind power generation scenario at t, the NG balance at gas node gn should be balanced.

$$\begin{aligned}\sum_{gw\in\Phi_{gn}^{GW}} G_{gw,t} + \sum_{gs\in\Phi_{gn}^{GS}} \left(S_{gs,t-1} - S_{gs,t}\right) + \sum_{gn'\in\Phi_{gn}^{GN}} F_{gn,gn',t,s} \\ - \sum_{gu\in\Phi_{gn}^{GF}} \left(L_{gu,t}\cdot EF_{gu}\right) - \left(L_{gn,t} - \Delta L_{gn,t,s}\right) = 0 \quad \forall gn,t,s\end{aligned} \tag{4}$$

Gas load shedding: For non-electrical loads, gas load shedding can be conducted to ensure gas balance with operating constraints. It is assumed that these gas loads can be dispatched continuously.

$$0 \le \Delta L_{gn,t,s} \le L_{gn,t} \qquad \forall t,gn,s \tag{5}$$

NG flow in pipelines not to be maintained: The pressure drops in pipelines are usually modeled as the nonlinear Weymouth (6).

$$\begin{aligned}\mathrm{sign}(F_{gn,gn',t,s})\cdot F_{gn,gn',t,s}^2 = C_{gn,gn'}^2\cdot(PS_{gn,t,s}^2 - PS_{gn',t,s}^2) \\ \forall gn,gn',t,s\end{aligned} \tag{6}$$

However, (6) is a nonlinear equation, which results in difficulty in solving the model. In this paper, a piecewise linear formulation by using mixed integer programming, is employed. Substitute PS^2 with π, and the left side of (6) is modeled as a piecewise linear function.

Gas node pressure: Considering the constraints of gas node pressure, the following inequalities should be satisfied.

$$\underline{\pi}_{gn} \le \pi_{gn,t,s} \le \bar{\pi}_{gn} \quad \forall gn,t,s \tag{7}$$

Compressors: For a pipeline with a compressor, the pressure of in-coming gas node gn is lower than the pressure of out-coming gas node gn'.

$$\pi_{gn',t,s} \le \lambda_{pc}\cdot\pi_{gn,t,s} \quad \forall pc,t,s,(gn,gn')\in pc \tag{8}$$

C. Power Grid

For a power grid, the operating constraints, i.e., power balance, ramping rates of generators, should be satisfied. The constraints are shown as follows.

$$\begin{aligned}B_{pn,pn'}\cdot\left(\theta_{pn,t,s} - \theta_{pn',t,s}\right) - P_{pn,pn',t,s}^L + (1-m_{l,t})\cdot M_l \ge 0 \\ \forall t,s,l,(pn,pn')\in l\end{aligned} \tag{9}$$

$$\begin{aligned}B_{pn,pn'}\cdot\left(\theta_{pn,t,s} - \theta_{pn',t,s}\right) - P_{pn,pn',t,s}^L - (1-m_{l,t})\cdot M_l \le 0 \\ \forall t,s,l,(pn,pn')\in l\end{aligned} \tag{10}$$

$$\begin{aligned}\underline{P}_{pn,pn'}^L\cdot m_{l,t} \le P_{pn,pn',t,s}^L \le \bar{P}_{pn,pn'}^L\cdot m_{l,t} \\ \forall t,l,s,(pn,pn')\in l\end{aligned} \tag{11}$$

$$B_{pn,pn'}\cdot\left(\theta_{pn,t,s} - \theta_{pn',t,s}\right) = P_{pn,pn',t,s}^L \quad \forall t,l',s,(pn,pn')\in l' \tag{12}$$

$$\underline{P}_{pn,pn'}^L \le P_{pn,pn',t,s}^L \le \bar{P}_{pn,pn'}^L \quad \forall t,l',s,(pn,pn')\in l' \tag{13}$$

$$\begin{aligned}\sum_{gu\in\Phi_{pn}^{GU}} P_{gu,t} + \sum_{wf\in\Phi_{pn}^{WF}} P_{wf,t,s} - \left(L_{pn,t} - \Delta L_{pn,t,s}\right) + \\ \sum_{pn'\in\Phi_{pn}^{PN}} P_{pn,pn',t,s}^L = 0 \qquad \forall t,s,pn\end{aligned} \tag{14}$$

$$P_{gu,t} = L_{gu,t}\cdot EF_{gu} \quad \forall gu\in\Phi_{gn}^{GF}, gn \tag{15}$$

$$\underline{\theta}_{pn} \le \theta_{pn,t,s} \le \bar{\theta}_{pn} \qquad \forall t,pn,s \tag{16}$$

$$0 \le \Delta L_{pn,t,s} \le L_{pn,t} \qquad \forall t,pn,s \tag{17}$$

$$\underline{P}_{gu} \le P_{gu,t} \le \bar{P}_{gu} \qquad \forall gu,t \tag{18}$$

$$P_{gu,t} - P_{gu,t-1} \le \bar{R}_{gu} \qquad \forall gu,t \tag{19}$$

$$P_{gu,t-1} - P_{gu,t} \le \underline{R}_{gu} \qquad \forall gu,t \tag{20}$$

$$P_{wf,t,s} \sim N\left(\mu_{wf,t}, {\sigma_{wf,t}}^2\right) \qquad \forall wf,t,s \tag{21}$$

Constraints (9) and (10) represent the physical relations between voltage angles and power flows in transmission lines to be maintained. M_l is a disjunctive parameter. With a sufficiently large M_l, (9) and (10) are redundant when the corresponding lines are under maintenance at t under wind power generation scenario s. For lines to be maintained, (11) ensures that power flows at t under scenario s satisfy lower and upper bounds. (12) presents the relation between voltage angles and power flows in lines, where no maintenance activity is needed in time periods, and (13) shows the corresponding capacity limits. (14) enforces power balance at each node at each time t under each wind power generation scenario s. (15) shows the relations between natural gas and real power from gas-fired units. (16) shows the lower and upper limits of the angle phase at each node in each period under each wind power generation scenario s. (17) enforces the lower and upper limits of load shedding. (18) shows the capacity limits of generators. (19) and (20) are the ramp-up and ramp-down constraints of generators, (21) denotes that the wind power satisfies a normal distribution.

D. Optimization Model

The objective of the optimization model is to minimize the operational costs and the penalties caused by non-served gas loads and power loads. The optimization model is formulated as follows.

$$\begin{aligned}\min\ & \underbrace{\sum_{l=1}^{N_{ML}}\sum_{t=1}^{N_T}\left(C_{l,t}^{M}\cdot m_{l,t}\right)}_{36.a}+\underbrace{\sum_{gu=1}^{N_{GU}}\sum_{t=1}^{N_T}\left(C_{gu,t}^{L}\cdot P_{gu,t}\right)}_{36.b}+\\ & \underbrace{\sum_{gw=1}^{N_{GW}}\sum_{t=1}^{N_T}\left(C_{gw,t}\cdot G_{gw,t}\right)}_{36.c}+\underbrace{\sum_{gs=1}^{N_{GS}}\sum_{t=1}^{N_T}\left(C_{gs,t}\cdot G_{gs,t}\right)}_{36.d}+\\ & \underbrace{\sum_{pn=1}^{N_{PN}}\sum_{t=1}^{N_T}\left(C_{pn,t}^{LS}\cdot\frac{1}{N_S}\sum_{s=1}^{N_S}\left(\Delta L_{pn,t,s}\right)\right)}_{36.e}+\\ & \underbrace{\sum_{gn=1}^{N_{GN}}\sum_{t=1}^{N_T}\left(C_{gn,t}^{LS}\cdot\frac{1}{N_S}\sum_{s=1}^{N_S}\left(\Delta L_{gn,t,s}\right)\right)}_{36.f}\end{aligned} \tag{22}$$

s.t.

$$m_{l,t-1}-m_{l,t}+m_{l,t'}\le 1 \qquad 1\le t'-(t-1)\le D_l^M\,,\forall l,t \tag{23}$$

$$\sum_{t=1}^{N_T}\left(1-m_{l,t}\right)=D_l^M \qquad \forall l \tag{24}$$

$$\sum_{l=1}^{N_{ML}}\left(1-m_{l,t}\right)\le \bar{N}_t^{L,M} \qquad \forall t \tag{25}$$

Constraints (1)-(8)

Constraints (9)-(21)

where (22.a) is the cost of transmission line maintenance, (22.b) is the operational cost of generating units, (22.c) and (22.d) are the operational costs of gas wells and gas storages, (22.e) is the cost of penalties caused by non-served power loads, and (22.f) is the cost of penalties caused by non-served gas loads. (23) ensures the minimal durations of maintenance activities on lines. (24) ensures that maintenance activities on lines will be implemented during the time periods. (25) ensures the maximum number of lines that can be maintained at one time period. The established model is a mixed integer linear program, which is solved by CPLEX solver in this paper.

III. Case Studies

In this section, a 6-bus system with a 4-node gas grid and a modified IEEE 118-bus system with a 20-node gas grid are employed to show the effectiveness of the proposed model. The cases are tested in MATLAB 2017 using the CPLEX solver on a personal computer with a 3.1 GHz i5 processor and 8 GB RAM.

A. Six-Bus System with Four-Node Gas Grid

1) Data description

The integrated system topology is shown in Fig. 1. The lower limits of outputs of the generators G_1, G_2 and G_3 are 100 MW, 80 MW and 150 MW, and their upper limits of outputs are 300 MW, 200 MW and 350 MW, respectively. Their maximum ramping rates are 25 MW/h, 20 MW/h and 7.5 MW/h. The minimum up periods are 4, 3 and 2, and the minimum down periods are 2, 3 and 3, respectively. The fixed costs of G_1, G_2 and G_3 at each time period are 5000 \$, 5100 \$ and 5150 \$, respectively. The linear costs of G_1, G_2 and G_3 are 11500 \$/MW, 10000 \$/MW and 11000 \$/MW. The costs of restarting G_1, G_2 and G_3 are 5000 \$, 4000 \$ and 6000 \$. The cost of power load shedding is 20000 \$/MW.

The lower limits of outputs of the gas wells W_1 and W_2 are 6000 m^3/h and 5000 m^3/h, and their upper limits of outputs are 90000 m^3/h and 80000 m^3/h, respectively. The costs of gas production and storage are 40 \$/m^3 and 2 \$/m^3. The efficiency factor of each gas-fired unit is assumed to be 0.004 MW/m^3.

During the 48 periods, the maintenance of the line 1-4 and the line 3-6 should be conducted, and the maintenance activities need 12 and 16 time periods, respectively. Their maintenance costs are 1000 \$ and 1200 \$ per time period. In addition, the maintenance of the pipeline 2-3 should be also conducted with 1000 \$ per time period, and the maintenance activities needs 15 time periods.

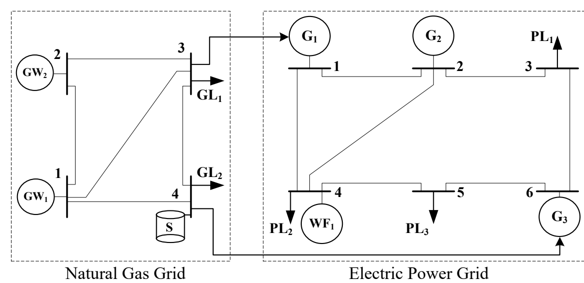

Fig. 1 A six-bus power system with a four-node gas grid

2) Maintenance scheduling

This section shows the maintenance scheduling of lines and pipelines. We assume 6% of each forecasted value as the volatility at each time period. Two-hundred wind power generation scenarios based on the LHS technique are used in the simulation. Fig. 2 shows two scenarios with different constraints about the maximum numbers of lines that can be maintained at one time period. For the scenario in Fig. 2 (a) and Fig. 2 (b), the maximum numbers of lines under maintenance are one and two, respectively. The objective values of the two scenarios are 5.882×10^8 and 5.579×10^8, respectively. Since the constraints of the scenario in Fig. 2 (b) are more relaxed than those in in Fig. 2 (a), its objective value is smaller than that of the scenario in Fig. 2 (a).

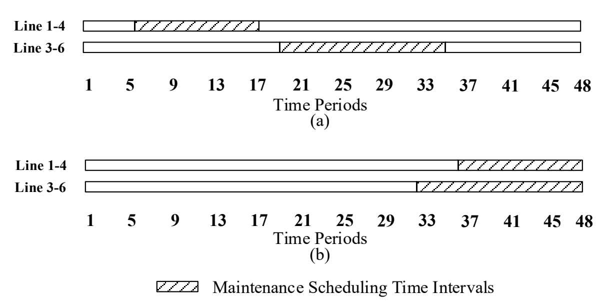

Fig. 2 (a) At most one line can be under maintenance at one time period. (b) At most two lines can be under maintenance at one time period.

3) *Influences of Piecewise Linear Approximation*

This section shows the influences of piecewise linear approximation on the maintenance scheduling. Fig. 3 shows the objective values of different numbers of piecewise lines. Results show that the approximation method with less piecewise lines has smaller objective values. The main reason is that less piecewise lines usually result in more relaxed bounds.

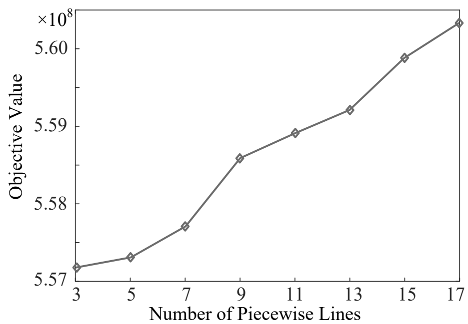

Fig. 3 Objective values of different numbers of piecewise lines

4) *Influences of LHS technique*

This section shows the influences of wind power generation methods, i.e., the Monte Carlo simulation with and without the LHS technique, on maintenance scheduling. Fig.4 (a) and (b) show the probability density functions with and without LHS technique. With the LHS technique, the mean and the variance are 5.868×10^8 and 2.708×10^5. Without the LHS technique, the mean and the variance are 5.885×10^8 and 4.114×10^5. Results show that Monte Carlo simulations with the LHS technique have better performance.

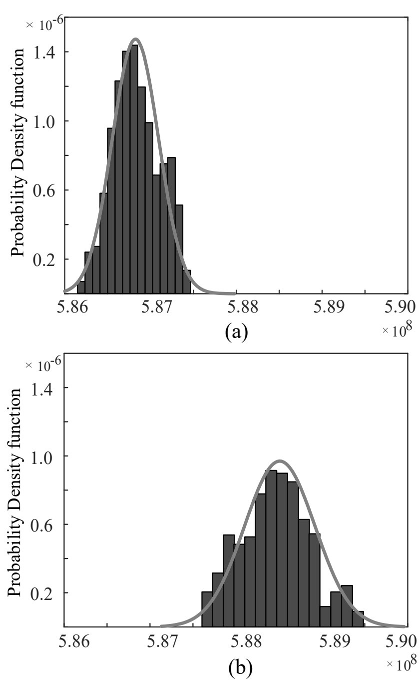

Fig. 4 (a) Monte Carlo simulation with the LHS technique with 6% forecasting errors of wind power. (b) Monte Carlo simulation without the LHS technique with 6% forecasting errors of wind power.

IV. Conclusion

In this paper, a stochastic security-constrained model to establish short-term maintenance strategies for integrated natural gas and electric grids with wind energy integration was proposed. The Latin hypercube sampling technique was used to simulate to represent wind power volatility. A piecewise linear approximation approach was employed to transform the models of natural gas grids into mixed integer linear models. A big-M formulation method was used to ensure power balance at each power node and gas node. The entire problem was modeled as a mixed integer linear programming problem. Simulations were carried out on a 6-bus system with a 4-node gas gird to validate the proposed model.

References

[1] M. Shahidehpour, Y. Fu, and T. Wiedman, “Impact of natural gas infrastructure on electric power systems,” *Proc. IEEE*, vol. 93, no. 5, pp.1042–1056, May 2005.

[2] C. Liu, M. Shahidehpour, Y. Fu and Z. Li, “Security-constrained unit commitment with natural gas transmission constraints,” *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1523-1536, Aug. 2009.

[3] S. K. Abeygunawardane, P. Jirutitijaroen, and H. Xu, “Adaptive maintenance policies for aging devices using a Markov decision process,” *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3194-3203, Aug. 2013.

[4] C. Wang, Y. Hou, Z. Qin, C. Peng, and H. Zhou, “Dynamic coordinated condition-based maintenance for multiple components with external conditions," *IEEE Trans. Power Del.,* vol. 30, no. 5, pp. 2362-2370, Oct. 2015.

[5] C. Wang and Y. Hou, "A novel method for optimal life cycle management scheme with Markov model," *2014 IEEE PES General Meeting | Conference & Exposition*, National Harbor, MD, 2014, pp. 1-5.

[6] C. Wang, H. Zhou, Y. Hou and H. Liu, "Dynamic maintenance strategies for multiple transformers with Markov models," *ISGT 2014*, Washington, DC, 2014, pp. 1-5.

[7] M. Puterman*, Markov Decision Process*. New York: Wiley, 1994, pp. 92-100.

[8] T. M. Welte, “Using state diagrams for modeling maintenance of deteriorating systems,” *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 58-66, Feb. 2009.

[9] E. L. Silva, M. T. Schilling, and M. C. Rafael, “Generation maintenance scheduling considering transmission constraints,’’ *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 838-843, May 2000.

[10] Y. Fu, S. M. Shahidehpour, and Z. Li, “Security-constrained optimal coordination of generation and transmission maintenance outage scheduling,” *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp.1302-1313, Aug. 2007.

[11] M. Shahidehpour and Y. Fu, “Benders decomposition - applying Benders decomposition to power systems,” *IEEE Power Energy Mag.*, vol. 3, no. 2, pp. 20–21, Mar./Apr. 2005.

[12] A. M. Geoffrion, “Generalized Benders decomposition,” Journal of Optimization Theory and Application, vol. 10, no. 4, pp. 237-261, 1972.

[13] A. J. Conejo, R. Garcia-Bertrand, and M. Diaz-Salazar, “Generation maintenance scheduling in restructured power systems,” *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 984-992, May 2005.

[14] H. Pandzic, A. J. Conejo, and I. Kuzle, “An EPEC approach to the yearly maintenance scheduling of generating units,” *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 922-930, May 2013.

[15] Y. Wang, D. S. Kirschen, H. Zhong, Q. Xia, and C. Kang, “Coordination of generation maintenance scheduling in electricity markets,” *in press*.

[16] F. Bouffard and F. D. Galiana, “Stochastic security for operations planning with significant wind power generation,” *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 306-316, May 2008.

[17] Y. Guan and J. Wang, “Uncertainty sets for robust unit commitment,” *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1439-1440, May 2014.