Short-Term Transmission Line Maintenance Scheduling with Wind Energy Integration

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***Abstract*— Transmission line maintenance scheduling (TLMS) plays an important role in enhancement of component reliability. When conducting short-term TLMS, system operators should consider not only operating costs but also operating constraints, particularly with increasing integration of large-scale wind generation. This paper proposes a stochastic security-constrained model to establish short-term TLMS in consideration of wind generation. Possible scenarios, generated by the Latin hypercube sampling (LHS) technique, are simulated to represent wind power volatility. For each line to be maintained during the maintenance windows, Kirchoff's law is enforced by using a big-M formulation. Unit commitment is also considered to coordinate TLMS to achieve the best maintenance strategies. The whole problem is modeled as a mixed integer linear programming problem, which is solved by the CPLEX solver. Numerical tests on a six-bus system and a modified IEEE 118-bus system show the effectiveness of the proposed model and the algorithm.**

***Index Terms*—Cost effective, cyber infrastructure, cyber security, probabilistic, updating strategy.**

NOMENCLATURE

Indices

i Index of generators
j Index of wind farms
k Index of lines to be maintained in time periods
k' Index of lines not to be maintained in time periods
n, n' Index of nodes
t, t' Index of time periods
s Index of wind power generation scenarios

Parameters

N_N Number of nodes
N_G Number of generators
N_W Number of wind farms
N_M Number of lines to be maintained in time periods
N_S Number of wind power generation scenarios
N_L Number of lines
N_T Number of time periods
D_k^M Duration of maintenance of line k
$N_t^{M,\max}$ Maximum number of lines under maintenance at t
$P_i^{\max}$ Maximum output of generator i (MW)
$P_i^{\min}$ Minimum output of generator i (MW)
R_i^{UP} Ramp-up limit of generator i
R_i^{DN} Ramp-up limit of generator i
D_i^{ON} Minimum on time periods of generator i
D_i^{OFF} Minimum off time periods of generator i
$C_{k,t}^M$ Maintenance cost of line k at t
$C_{i,t}^F$ Fixed cost of online generator i at t
$C_{i,t}^L$ Linear cost of online generator i at t
$C_{i,t}^S$ Start up cost of generator i at t
$C_{n,t}^{LS}$ Cost of load shedding of node n at t
$L_{n,t}$ Load demand of node n at t
$B_{n',n}$ Electrical susceptance of line $n'-n$
$P_{n,n'}^{L,\max}$ Maximum capacity of line $n'-n$
$P_{n,n'}^{L,\min}$ Minimum capacity of line $n'-n$
M_k Large number
Φ_n^G Set of generators connected with node n
Φ_n^W Set of wind farms connected with node n
Φ_n^D Set of loads connected with node n
Φ_n^N Set of nodes connected with node n

Variables

$m_{k,t}$ Binary variable to indicate if transmission line k is under maintenance at t. 1 denotes maintenance, otherwise 0.

This work is partly supported by.

$o_{i,t}$ Binary variable to indicate status of generator i at t. 1 and 0 denote on-status and off-status

$u_{i,t}$ Binary variable to indicate if generator i started up at t.

$P_{i,t}^{G}$ Power generation of generator i at t

$P_{n,n',t,s}^{L}$ Real power from node n to n' at t under scenario s

$\theta_{n,t,s}$ Phase angle of node n at t under scenario s

$\Delta L_{n,t,s}$ Load shedding of node n at t under scenario s

I. INTRODUCTION

High reliability of each transmission line is a guarantee for the safe operations of power systems. Usually, system operators enhance reliability of transmission lines via maintenance. According to different time spans, transmission lines maintenance scheduling (TLMS) can be divided into two categories, i.e., long-term TLMS and short-term TLMS. Long-term TLMS is required to satisfy weekly constraints, seasonal constraints and the system energy in each interval. Based on the maintenance window from long-term TLMS, short-term TLMS is required to minimize the loss of revenue while satisfying the operating conditions, typically with increasing integration of large-scale wind generation. The International Energy Agency (IEA) has reported that more than 6.5% of word electricity will be generated from wind [1], and 20% of electricity will be generated by wind in the United States by 2030 [2]. Uncertainty caused by highly penetrating wind power has brought great challenges to power system operations, typically in the face of short-term TLMS associated with system topology changes. Therefore, it is critical to make short-term TLMS to achieve the best system performance in consideration of wind power.

At present, many models, e.g., Markov-based models and MILP-based models, are proposed to establish maintenance strategies of electric devices. Considering uncertainties of deterioration processes of devices, a Markov model is introduced to represent deterioration processes to establish optimal maintenance policy [3] . To include the influences of external harsh weather events, a probabilistic model associated with a Markov model is proposed to establish maintenance strategies in [4]. A backward induction [5] with a search space reduction method is employed to improve computational efficiency while still maintaining good accuracy. In addition to Markov models, some models [6] based on mixed integer linear programming are proposed to schedule maintenance activities on electric devices. In these models, the status of each device to be maintained works as a binary variable, with the objective of minimizing the revenue losses and the operating costs. To solve these MILP models, many methods, e.g., the Benders decomposition method [7], are employed. The above studies are based on a centralized power system. With the developments of electricity markets, there are multiple independent transmission companies (TRANSCOs) and generation companies (GENCOs). The conventional maintenance strategies from the centralized framework are not suitable in the electricity markets. In [8], an iterative procedure to coordinate generation maintenance scheduling between an independent system operator (ISO) and GENCOs is proposed to achieve an acceptable system reliability. The iterative procedure depends on a tuned-up incentive and disincentive mechanism. In [9], a bilevel model is proposed to establish yearly maintenance scheduling of generators in a market environment. For each GENCO, its problem is modeled as a mathematical program with equilibrium constraints. [10] proposes a coordination mechanism for generation maintenance scheduling within market environments. A relaxation reduction algorithm is utilized to solve the proposed large mixed integer programming problem. However, few research studies consider the influences of wind power on maintenance scheduling, typically on short-term transmission line maintenance scheduling.

In this paper, a stochastic security-constrained model to establish short-term TLMS in consideration of wind generation is proposed. Possible scenarios, generated by the Latin hypercube sampling (LHS) technique, are simulated to represent wind power volatility. For each line to be maintained during the maintenance windows, Kirchoff's law is enforced by using a big-M formulation. Unit commitment is also included to coordinate TLMS to achieve the best maintenance strategies, considering operating constraints, such as power balance, line capacities and generators' ramping rates. The whole problem is modeled as a mixed integer linear programming problem, which is solved by the CPLEX solver. Numerical tests on a six-bus system and a modified IEEE 118-bus system show the effectiveness of the proposed model and the algorithm.

The remainder of this paper is organized as follows. Section II shows the maintenance scheduling formulation with wind energy integration. Section III introduces the solution method. Section IV presents the case studies, and the work is concluded in Section V.

II. MAINTENANCE SCHEDULING FORMULATION WITH WIND ENERGY INTEGRATION

A. Scenario Generation

Wind power generation at each time period is assumed to satisfy a normal distribution.

$$P_{j,t}^{W} : \ N\left(\mu_{j,t}, \sigma_{j,t}^{\ 2}\right) \qquad \forall j,t \tag{1}$$

Since the Monte Carlo simulation method needs a large number of scenarios to get a reasonably accurate random distribution, Latin hypercube sampling (LHS) technique is employed to achieve a satisfied accuracy with reduced scenarios.

B. Maintenance Scheduling Model

The short-term maintenance scheduling should consider the economy and system operating requirements. Considering changed system topologies due to line maintenance, unit commitment should be included to guarantee the system operating requirements. The maintenance scheduling model is represented as follows.

$$
\begin{aligned}
\min \quad & \sum_{k=1}^{N_M}\sum_{t=1}^{N_T}\left(C_{k,t}^{M}\cdot m_{k,t}\right)+ \\
& \sum_{i=1}^{N_G}\sum_{t=1}^{N_T}\left(C_{i,t}^{F}\cdot o_{i,t}+C_{i,t}^{L}\cdot P_{i,t}+C_{i,t}^{S}\cdot u_{i,t}\right)+ \\
& \sum_{n=1}^{N_N}\sum_{t=1}^{N_T}\left(C_{n,t}^{LS}\cdot\frac{1}{N_S}\sum_{s=1}^{N_S}\left(\Delta L_{n,t,s}\right)\right)
\end{aligned}
\tag{2}
$$

s.t.

$$m_{k,t-1}-m_{k,t}+m_{k,t'}\le 1 \qquad 1\le t'-(t-1)\le D_k^{m},\forall k,t \tag{3}$$

$$\sum_{t=1}^{N_T}\left(1-m_{k,t}\right)=D_k^{M} \qquad \forall k \tag{4}$$

$$\sum_{t=1}^{N_M}\left(1-m_{k,t}\right)=N_t^{M,\max} \qquad \forall t \tag{5}$$

$$
\begin{aligned}
& B_{n,n'}\cdot\left(\theta_{n,t,s}-\theta_{n',t,s}\right)-P_{n,n',t,s}^{L}+(1-m_{k,t})\cdot M_k\ge 0 \\
& \qquad\qquad n,n'\in Line_k,\forall t,k,s
\end{aligned}
\tag{6}
$$

$$
\begin{aligned}
& B_{n,n'}\cdot\left(\theta_{n,t,s}-\theta_{n',t,s}\right)-P_{n,n',t,s}^{L}-(1-m_{k,t})\cdot M_k\le 0 \\
& \qquad\qquad n,n'\in Line_k,\forall t,k,s
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
& P_{n,n'}^{L,\min}\cdot m_{k,t}\le P_{n,n',t,s}^{L}\le P_{n,n'}^{L,\max}\cdot m_{k,t} \\
& \qquad\qquad n,n'\in Line_k,\forall t,k,s
\end{aligned}
\tag{8}
$$

$$B_{n,n'}\cdot\left(\theta_{n,t,s}-\theta_{n',t,s}\right)=P_{n,n',t,s}^{L} \qquad n,n'\in Line_{k'},\forall t,k',s \tag{9}$$

$$P_{n,n'}^{L,\min}\le P_{n,n',t,s}^{L}\le P_{n,n'}^{L,\max} \qquad n,n'\in Line_{k'},\forall t,k',s \tag{10}$$

$$-o_{i,t-1}+o_{i,t}-o_{i,t'}\le 0 \qquad 1\le t'-(t-1)\le D_i^{ON},\forall i,t \tag{11}$$

$$o_{i,t-1}-o_{i,t}+o_{i,t'}\le 1 \qquad 1\le t'-(t-1)\le D_i^{OFF},\forall i,t \tag{12}$$

$$-o_{i,t-1}+o_{i,t}-u_{i,t}\le 0 \qquad \forall i,t \tag{13}$$

$$
\begin{aligned}
& \sum_{i\in\Phi_n^G}P_{i,t}^{G}+\sum_{j\in\Phi_n^W}P_{j,t}^{W}-\sum_{n\in\Phi_n^D}\left(L_{n,t}-\Delta L_{n,t,s}\right)+ \\
& \qquad\qquad \sum_{n'\in\Phi_n^N}P_{n,n',t,s}^{L}=0 \qquad \forall t,s,n
\end{aligned}
\tag{14}
$$

$$\theta_n^{\min}\le\theta_{n,t,s}\le\theta_n^{\max} \qquad \forall t,n,s \tag{15}$$

$$0\le\Delta L_{n,t,s}\le L_{n,t} \qquad \forall t,n,s \tag{16}$$

$$P_i^{\min}\cdot o_{i,t}\le P_{i,t}^{G}\le P_i^{\max}\cdot o_{i,t} \qquad \forall i,t \tag{17}$$

$$
\begin{aligned}
& P_{i,t}^{G}-P_{i,t-1}^{G}\le(2-o_{i,t-1}-o_{i,t})\cdot P_i^{\min}+ \\
& \qquad\qquad +(1+o_{i,t-1}-o_{i,t})\cdot R_i^{UP} \qquad \forall i,t
\end{aligned}
\tag{18}
$$

$$
\begin{aligned}
& P_{i,t-1}^{G}-P_{i,t}^{G}\le(2-o_{i,t-1}-o_{i,t})\cdot P_i^{\min}+ \\
& \qquad\qquad +(1-o_{i,t-1}+o_{i,t})\cdot R_i^{DN} \qquad \forall i,t
\end{aligned}
\tag{19}
$$

$$m_{k,t},o_{i,t},u_{i,t}\in\{0,1\} \qquad \forall k,i,t \tag{20}$$

The first term of (2) is the cost of maintenance scheduling. the second term of (2) includes the fixed cost of online generators, the varied cost regarding generators' outputs and the start-up cost of generators. The third term of (2) is the expected cost of load shedding under different wind power generation scenarios. Constraint (3) ensures the minimal duration of a maintenance activity. With (4), a maintenance activity can be guaranteed to be performed on the lines, which are scheduled to be maintained during the time periods. Constraint (5) ensures that maintenance activities can be performed on maximum lines at one time period. The physical relations between voltage angles and power flows in lines to be maintained are presented by constraints (6) and (7). M is a disjunctive parameter. With a sufficiently large M, (6) and (7) are redundant when the corresponding lines are under maintenance at *t* under wind power generation scenario *s*. For lines to be maintained, (8) ensure that power flows at *t* under scenario *s* satisfy lower and upper bounds. (9) presents the relation between voltage angles and power flows in lines, which need not maintenance activities in time periods, and (10) shows the corresponding capacity limits. (11) is the minimum on time constraint. (12) is the minimum off time constraint. (13) is the start-up constraint. Equation (14) enforces power balance at each node at each time *t* under each wind power generation scenario *s*. (15) shows the lower and upper limits of angle phases at each node in each period under each wind power generation scenario *s*. (16) enforces the lower and upper limits of load shedding. (17) shows the capacity limits of generators. (18) and (19) are ramp-up and ramp-down constraints of generators, respectively. (20) shows the binary constraints.

The established model is a mixed integer linear programming, which is solved by CPLEX solver in this paper.

III. Optimization Model Case Studies

In this section, a 6-bus system and a modified IEEE 118-bus system are employed to show the effectiveness of the proposed model. The influences of capacities of wind power, errors of wind power forecast, wind power scenarios and scenario generation methods are analyzed.

C. Six-Bus System

1) Data Description

The six-bus system is constructed based on a test system in [11]. The system topology is shown in Figure 1. We focus on 48 time periods, with two hours as one time period. The forecast wind power generation is shown in Figure 2. The trend of wind power generation refers to Belgian wind-power forecasting from 21st to 24th April 2016 [12].

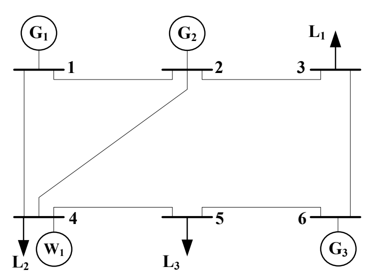

Figure 1. System topology

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 1000$, 1100$ and 1150$, respectively. The linear costs of G_1, G_2 and G_3 are 115$/MW, 100$/MW and 110$/MW. The costs of restarting G_1, G_2 and G_3 are 1040$, 1020$ and 1030$. The cost of load shedding is 1000$/MW. 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.

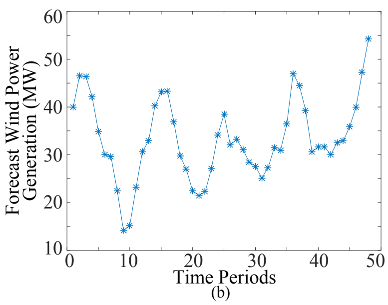

Figure 2. Forecast wind power

2) Maintenance scheduling

This section shows the maintenance scheduling. We assume 10% of each forecasted value as the volatility at each time period. One thousand wind power generation scenarios based on the LHS technique are used. Figure 3 shows two scenarios with different constraints about the maximum number of lines that can be maintained at one time period.

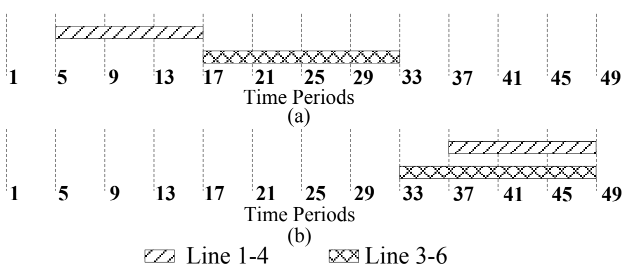

Figure 3. (a) At most one line can be under maintenance at one time period. (b) At most two lines can be under maintenance at one time period.

3) Influences of forecast errors and wind power generation scenarios

This section shows the influences of forecast errors and wind power generation scenarios. Figure 4 shows the objective values regarding forecast errors and wind power generation scenarios. Results show that larger forecast errors lead to larger objective values. The reason for larger objective values is potential larger load shedding due to severe wind power fluctuations under the condition of larger forecast errors.

Figure 5 shows relative errors regarding different wind power generation scenarios and forecast errors. When calculating relative errors for a forecast error and given wind power generation scenarios, the results based on one thousand wind power generation scenarios are reference values. The relative errors tend to be larger with less wind power generation scenarios and larger forecast errors, and tend to be smaller with more wind power generation scenarios and smaller forecast errors.

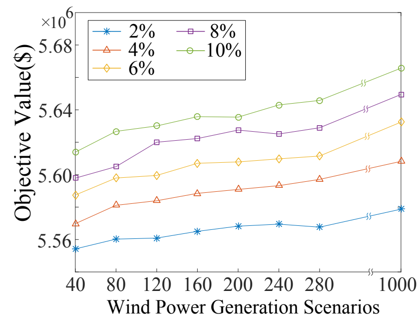

Figure 4. Objective values with different forecast errors and wind power generation scenarios

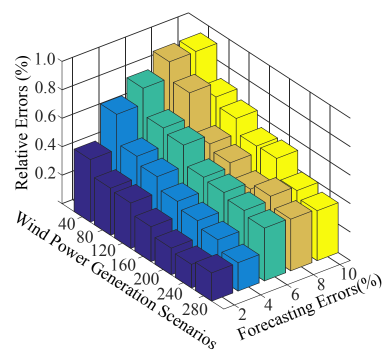

Figure 5. Relative errors regarding different wind power generation scenarios and forecast errors

4) Influences of wind power capacity

This section shows the influences of wind power capacities on maintenance scheduling. Figure 6 (a) shows relative errors regarding different wind power capacities and wind power generation scenarios under 10% forecast errors. The relative errors tend to be larger with less wind power generation scenarios and larger wind power capacities, and tend to be smaller with more wind power generation scenarios and less wind power capacities. Figure 6 (b) shows relative errors regarding different wind power capacities and wind power generation scenarios under 2% forecast errors. The relative errors regarding wind power capacities and wind power generation scenarios have the same tendency with the 10% forecasting errors. In addition, less forecasting errors have smaller relative errors.

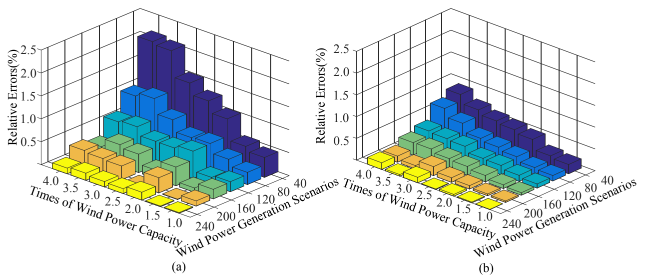

Figure 6. (a) Relative errors regarding different wind power capacities and wind power generation scenarios under 10% forecast errors. (b) Relative errors regarding different wind power capacities and wind power generation scenarios under 2% forecast errors

D. *Modified IEEE 118-Bus System*

1) *Data Description*

The IEEE 118-bus system contains 19 generators, 177 transmission lines, 9 transformers and 91 loads. The ramping rates of all generators are assumed to be 80MW/h. During a time window of 48 periods, five lines 69-47, 69-70, 69-75, 69-68 and 69-49 should be maintained. The wind power is referred to [13]. The minimum downtime and uptime of each generator are five time periods. The maintenance scheduling window of each line is 16 time periods.

2) *Simulation Results*

Based on the established model, the optimal maintenance activities on lines 47-69, 49-69, 68-69, 69-70, and 69-75 are shown in Figure 7. The objective is 2.219×10^7 \$. Figure 8 shows the on/off states of generators. When all generators can not be scheduled, the objective is 3.114×10^7 \$, which is much higher than 2.219×10^7 \$. Results show that the maintenance scheduling associated with appropriate on/off states of generators can achieve the optimal performance of the system.

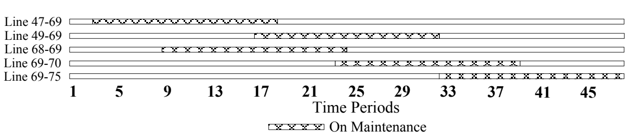

Figure 7. Maintenance Scheduling

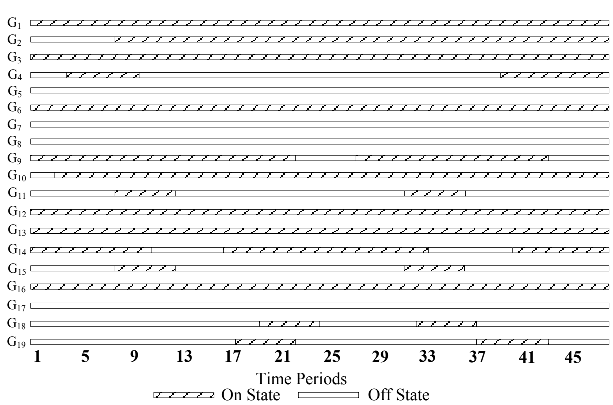

Figure 8. On/Off states of generators

IV CONCLUSION

This paper proposes a stochastic security-constrained model to establish short-term TLMS in consideration of wind generation. Wind generation scenarios from the LHS technique were generated to represent wind power volatility. The big-M formulation was employed to represent topology changes due to line maintenance. Unit commitment was included to coordinate TLMS to achieve the best maintenance strategies. The problem was modeled as a mixed integer linear programming problem, which was solved by the Benders decomposition method. The major findings are as follows. 1) Wind generation scenarios generated by the Latin hypercube sampling (LHS) technique have higher accuracy than those generated by conventional Monte Carlo simulations. 2) The big-M formulation can easily deal with the topology changes due to line maintenance.

REFERENCES

[1] Global Wind Energy Council, Global Wind Report Annual Market Update 2013 [Online]. Available: http://www.gwec.net/wp-content/uploads/2014/04/GWEC-Global-Wind-Report_9-April-2014.pdf

[2] U.S. National Renewable Energy Laboratory, 20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply Available: http://www.nrel.gov/docs/fy08osti/41869.pdf

[3] S. K. Abeygunawardane and P. Jirutitijaroen, "New state diagrams for probabilistic maintenance models," *IEEE Trans. Power Syst.,* vol. 26, no. 4, pp. 2207-2213, Nov. 2011.

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

[6] 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.

[7] 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.

[8] 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.

[9] 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.

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

[11] Q. F. Wang, Y. P. Guan, and J. H. Wang, "A chance-constrained two stage stochastic program for unit commitment with uncertain wind power output," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 206-215, Feb. 2012.

[12] Wind Power Data. [Online]. Available: http://www.elia.be/en/grid-data/power-generation/wind-power.

[13] J. Usaola, "Probabilistic load flow with correlated wind power injections," Electr. Pow. Syst. Res., vol. 80, no. 5, pp. 528–536, 2010.