ATLANTIS PRESS

Advances in Engineering Research, volume 112

4th International Conference on Renewable Energy and Environmental Technology (ICREET 2016)

A Comparative Study of Deterministic Unit Commitment and Probabilistic Unit Commitment

Gang ZHOU[1, a], Kaifeng ZHANG[1, b], Kun YUAN[1, c], Dawei LI[1, d], Qia DING[2, e], Lirong XIE[2,f] and Shuomin WU[1, g]

[1]Key Laboratory of Measurement and Control of CSE School of Automation, Southeast University Nanjing, China

[2]NARI Group Corporation, Nanjing, China

[a]kevin_zhougang@163.com, [b]kaifengzhang@seu.edu.cn, [c]kyuan@seu.edu.cn, [d]1370776342@qq.com, [e]dingqia@sgepri.sgcc.com.cn, [f]xielirong@sgepri.sgcc.com.cn, [g]546669176@qq.com.

Keywords: Deterministic unit commitment; Probability unit commitment; Irregular distribution of wind power; Wind scenarios; Scenarios check.

Abstract. According to the influence of wind power integration on the security and stability of power system, deterministic unit commitment is currently used to economic dispatch, which takes reserve capacities to cope with the wind power fluctuation. Compared with the traditional deterministic unit commitment, this paper adopts the scenario-based method to build the probabilistic unit commitment model. A method of wind irregular probabilistic distribution model based on "wind speed-wind power" relationship is proposed to describe the uncertainty of wind power with multiple scenarios. The paper has deeply research on the similarities and differences of deterministic unit commitment and probabilistic unit commitment, and analyzes the influence of two scheduling schemes on the system operation cost, solving efficiency and the ability of system acceptance wind power, respectively. A modified IEEE 118-bus test system is used to make simulation and verification, comparison results of two method provide strong technical support for the engineering community to the operation of probabilistic unit commitment.

Introduction

As an eco-friendly and renewable energy, wind power has more long-term environmental and economic benefits than traditional power generation. However, considering the volatility , intermittency and un-dispatching ability of wind power, its large-scale connection to electricity grid will greatly challenge power system stability and grid dispatching.

Currently, according to the influence of wind power integration, deterministic unit commitment is usually used to economic dispatch [1, 2]. Deterministic unit commitment is based on the traditional unit commitment model, and takes the wind power forecast provided by the dispatching department as scenario of wind power output. The forecast error and probabilistic distribution of wind power output are not considered in deterministic unit commitment, spinning reserve is used to cope with the fluctuation of wind power. The generation schedule is relatively conservative, so adequate reserve capacity should be set aside to deal with the uncertainty of wind power. Reference [3, 4, 5] study the electric power system economic dispatch in a single period. According to the probability distribution of wind power prediction error, the second reserve capacity needed can be computed in preset wind power confidence, which can cope with the possible dispatch of wind power surplus or shortage.

A lot of research has been conducted on the power system safety check and unit commitment technology for large-scale wind power integration, the stochastic optimized models and methods such as scenario analysis method, chance-constrained programming model and interval-based optimization method are proposed. As a stochastic and uncertain unit commitment, the probabilistic unit commitment based on scenarios analysis method is used to deal with unit commitment problem containing wind power, which transforms uncertainty problem containing random variable into deterministic problem with multiple scenarios [6, 7]. The wind power uncertainty can be represented by forecast wind power scene and the wind power probability error scenarios, which are generated Monte Carlo scenario method based on wind irregularly probabilistic distribution. This method can accurately consider the uncertainty of wind power through a large number of scenarios, however, it has a high computational complexity in mathematics. It is difficult to understand and accept the direct application to scheduling and safety check in engineering. Essentially, the deterministic unit commitment is a special case of the probabilistic unit commitment only considering forecast wind power scenario, the solving efficiency is high and applicability is more extensive at present. However, the power generation plan is relatively conservative and weak in wind power fluctuation.

In this paper, in order to compare deterministic unit commitment and probabilistic unit commitment deeply, the two models are established respectively. In the probabilistic unit commitment, a method of wind power error distribution based on wind speed prediction error distribution is proposed, which can determine the distribution of wind power by the “wind speed-wind power” curve of the wind turbine. The paper presents a deep comparison between deterministic unit commitment and probabilistic unit commitment and analyze the cost and the solving efficiency of two scheduling schemes. Based on two schemes, a large amount wind scenarios were generated by Monte Carlo scenario method, which were used to check the ability of two scheduling schemes to respond to wind power fluctuation, respectively. The simulation results provide a powerful technical support for exploring the feasibility of taking into account the uncertainty of wind power, the operation characteristics of power system and the operability of dispatching operation, so as to enhance the safe and economical operation level of power system.

Model Formulation

Deterministic Unit Commitment model. The deterministic unit commitment only considers the wind power forecasting output and does not consider the uncertainty of the wind power directly. After considering certain constraints, the output scheme and startup and shutdown scheme of units can be planned for a certain time scale. The optimization objective is to minimize the operation cost. The objection function (1) is composed of fuel costs for producing electric power, and startup and shutdown costs of individual units.

$$Min \sum_{i=1}^{NG}\sum_{t=1}^{NT} F_{ci}(P_{it}) \cdot I_{it} + I_{it}(1-I_{it-1}) \cdot SU_i + I_{it}(1-I_{it-1}) \cdot SD_i \tag{1}$$

Where NT is number of periods (24 h). NG is number of non-wind units. P_{it} is generation of unit i at time t. I_{it} is state of unit i at time t. SU_i and SD_i are startup cost and shutdown cost. $F_{ci}(P_{it})$ is operation cost of units, which are shown in (2).

$$F_{ci}(P_i) = a_i + b_i \cdot P_i + c_i \cdot P_i^2 \tag{2}$$

Where a_i, b_i and c_i are parameters of operation costs.

The constrains of deterministic unit commitment are listed below include the system power balance constraints (3), system spinning reserve requirements (4), units ramping up limits (5)(6), units minimum ON time and OFF time limits (7)(8), units generation limits (9), and generalized network constraints (10).

$$\sum_{i=1}^{NG} P_{it} * I_{it} + \sum_{k=1}^{NW} P_{k,t} = P_{L,t} \quad (t = 1, ..., NT) \tag{3}$$

$$\sum_{i=1}^{NG} P_{\mathrm{i,max}} * I_{it} \geq R_t + P_{L,t} \quad (t = 1, ..., NT) \tag{4}$$

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

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

$$[X^{on}{}_{i(t-1)} - T^{on}{}_{i}]*[I_{i(t-1)} - I_{it}] \geq 0 \quad (i = 1,...,NG; t = 1,...,NT) \tag{7}$$

$$[X^{on}{}_{i(t-1)} - T^{on}{}_{i}]*[I_{i(t-1)} - I_{it}] \geq 0 \quad (i = 1,...,NG; t = 1,...,NT) \tag{8}$$

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

$$G(P_{it}, P^{c}_{w,k}) \leq 0 \quad (i = 1,..., NG; t = 1,..., NT; k = 1,..., NW) \tag{10}$$

Where NW is number of wind power units, P_{kt} is generation of wind farm k at time t, $P_{L,t}$ is system load demand at time t, $P_{i,\max}$ is upper limit power generation of unit i, R_t is system spinning reserve requirement at time t, UR_i, DR_i are ramp-up and ramp-down rate limit of unit i, $P_{i,\min}$ is lower limit power generation of unit i, $X^{on}{}_{i(t-1)}$ and $X^{off}{}_{i(t-1)}$ are ON time and OFF time of unit i at time t, $T^{on}{}_{i}$ and $T^{off}{}_{i}$ are minimum ON and OFF time at time t, $G(\bullet)$ are generalized network constraints.

Probabilistic Unit Commitment Model.

Compared with the deterministic unit commitment, the probability unit combination directly takes into account the forecast error and probability distribution of the wind power and uses the scenario method to convert the uncertainty problem into the deterministic problem involving multiple wind scenarios, which can be solved directly.

A. Modeling of Irregular Distribution of Wind Power.

According to the forecast error of wind power, several empirical distribution models, such as normal distribution, beta distribution, Cauchy distribution and Laplacian distribution, have been put forward at home and abroad [8, 9]. Due to the difference of wind farm scale and prediction method, the error distribution may be fuzzy, or biased. It is difficult to make a definite stipulation on the distribution of wind power forecasting error. With the deep research and a large number of statistics [10], it is found that wind speed prediction error is close to the normal distribution (11), as is shown in Fig. 1.

$$f(V) = \frac{1}{\sqrt{2p}\,s} e^{-\frac{(V - V_{pre})^2}{2s^2}} \tag{11}$$

Where V_{pre} is forecast wind speed, s is the standard deviation of the wind power output.

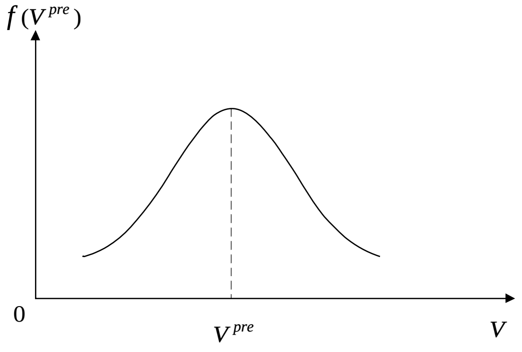

Fig. 1 Wind power output distribution curve

“Wind speed-wind power” characteristic curve of the wind turbine is shown in Fig. 2. According to the distribution of the wind speed prediction error Eq. 11, the probability distribution of wind power can be obtained (12).

$$f\left(P_w,V\right)=\begin{cases}\left(\dfrac{1}{\sqrt{2\pi}\sigma}\displaystyle\int_{-\infty}^{V_{in}}\exp\left(-\dfrac{\left(V-V_{pre}\right)^2}{2\sigma^2}\right)dV+\dfrac{1}{\sqrt{2\pi}\sigma}\displaystyle\int_{V_{out}}^{+\infty}\exp\left(-\dfrac{\left(V-V_{pre}\right)^2}{2\sigma^2}\right)dV\right)\delta\left(P_w\right), & P_w=0\\ \dfrac{1}{\sqrt{2\pi}\sigma}\exp\left(-\dfrac{\left(V-V_{pre}\right)^2}{2\sigma^2}\right), & P_w=a_0+a_1V+a_2V^2+a_3V^3\\ \left(\dfrac{1}{\sqrt{2\pi}\sigma}\displaystyle\int_{V_r}^{V_{out}}\exp\left(-\dfrac{\left(V-V_{pre}\right)^2}{2\sigma^2}\right)dV\right)\delta\left(P_w\right), & P_w=P_r\end{cases} \tag{12}$$

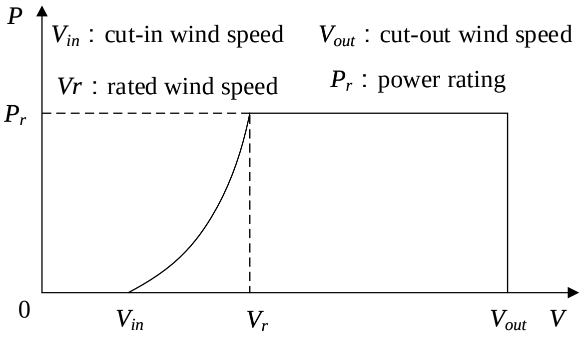

Fig. 2 “ Wind speed-wind power” characteristic curve of the wind turbine

Where P_w is output of the wind turbine when the wind speed is V .

B. Modeling of Probabilistic Unit Commitment.

Different from deterministic unit commitment, probabilistic unit commitment takes into account the uncertainty of wind power. In view of the established model of irregular wind power output, the wind power scenarios representing the wind power uncertainty are generated based on Monte Carlo scenario method, and the probability unit commitment considering wind power prediction error is established.

Probabilistic unit commitment model based on the deterministic unit commitment model, the objective function is kept unchanged and the wind power scenario constraints (13)-(16) are added to the constraint condition.

$$\sum_{i=1}^{NG}P_{it}^s*I_{it}+\sum_{k=1}^{NW}P_{w,kt}^s=P_{L,t}\qquad (t=1,...,NT) \tag{13}$$

$$|P_{it}^s-P_{it}|\le\Delta_i\qquad (i=1,...,NG;t=1,...,NT) \tag{14}$$

$$P_{i,\min}*I_{it}\le P_{it}^s\le P_{i,\max}*I_{it}\qquad (i=1,...,NG;t=1,...,NT) \tag{15}$$

$$G(P_{it}^s,P_{w,kt}^s)\le 0\qquad (i=1,...,NG;t=1,...,NT;k=1,...,NW) \tag{16}$$

Where $P_{W,kt}^s$ is simulated generation of wind power unit i at time in scenario s .

Model Solving

For the deterministic unit commitment, the objective function and constrains (7) and constrains (8) using the method in Reference [11, 12], and the optimization model is transformed into a mixed-integer linear optimization problem, which can be solved directly by commercial optimization software.

The probabilistic unit commitment is based on scenario analysis method to describe the uncertainty of wind power, so the solution size will increase with the number of scenes. In the paper, the Benders decomposition technique is applied to decompose such an optimization problem into the master unit commitment problem, network security check subproblem, and scenario feasibility check subproblem

[13]. Fig. 3 shows the flowchart of the proposed algorithm in which the forecasted wind power generation is given in the day-ahead scheduling.

A. Master unit commitment problem

The master unit commitment problem, which is composed of the objective function (1) and constrains (3)-(9), provides a commitment and dispatch solution that minimizes the operating cost of non-wind units by utilizing the forecast wind power generation. The wind power output scenarios are not considered in the problem, so the model scale is relatively small. At this point, the master unit commitment problem is a deterministic unit commitment.

B. Network security check subproblem

The network security check subproblem (17)–(25) is used for correcting transmission overflows based on dc power flow equations. In order to check transmission flows and gain a feasible solution in the case of flow violations, slack variables are added to transmission constraints.

$$Min\ w(\hat{I},\hat{P}_g)=\sum_{l=1}^{NL}(C_{l,1}+C_{l,2}) \tag{17}$$

$$(PL_l-C_{l,1})\le PL_{l,\max} \tag{18}$$

$$-(PL_l+C_{l,2})\le PL_{l,\max} \tag{19}$$

$$-\infty\le PL_l\le+\infty \tag{20}$$

$$P^{sp}=\hat{P}_g\ \hat{I}\quad \boldsymbol{\pi} \tag{21}$$

$$d_{\mathrm{ref}}=0 \tag{22}$$

$$g_{\min}\le g\le g_{\max} \tag{23}$$

$$B*\boldsymbol{\delta}=P^{sp}+P_w-P_L \tag{24}$$

$$PL_l=\frac{d_k-d_m-g_{\mathrm{km}}}{X_{\mathrm{km}}}\ \left(k,m\in l\right) \tag{25}$$

Where w is transmission flow violations.

The network security check subproblem can check the solutions solved in the master unit commitment problem, and guarantee that transmission flow violations are less than preset value, or Benders cut (26) will be added to the master problem.

$$w(P,I)=\hat{w}-\sum_{i=1}^{NG}(p_{it}^1-p_{it}^2)*(P_{it}-\hat{P}_{it})\le 0 \tag{26}$$

C. Scenario feasibility check subproblem

The scenario feasibility check subproblem will check whether the current commitment and dispatch solution of the master problem can accommodate the volatility of wind power in individual scenarios (27)–(30).

$$Min\quad v^s=\sum_{i=1}^{NG}\sum_{t=1}^{NT}(S1_{it}^s+S2_{it}^s+S3_{it}^s+S4_{it}^s) \tag{27}$$

$$\sum_{i=1}^{NG}R^s{}_{S,it}*\hat{I}_{it}+S3^s{}_t\ge R_{S,t}\ \ (t=1,\ldots,NT)\qquad l_3 \tag{28}$$

$$\left|P_{it}^s-\hat{P}_{it}\right|-S4_{it}^s\le\Delta_i\ (i=1,\ldots,NG;t=1,\ldots,NT) \tag{29}$$

$$\begin{cases}P_{it}^s\le P_{i,\max}*\hat{I}_{it} & l_1\\ P_{it}^s\ge P_{i,\min}*\hat{I}_{it} & l_2\end{cases}\quad (i=1,\ldots,NG;t=1,\ldots,NT) \tag{30}$$

Where $S1_t^s$, $S2_t^s$, $S3_t^s$ and $S4_t^s$ are slack variables, l_1, l_2 and l_3 are corresponding dual factors.

A positive value of the objective function means the commitment and dispatch solution of the master unit commitment problem cannot accommodate the wind power volatility for a specific scenario, in which case a Benders cut (31) will be generated and added to the master unit commitment problem for the next iteration.

$$v^s(P) = \hat{v}^s + \sum_{i=1}^{NG}\sum_{t=1}^{NT}(I_{it} - \hat{I}_{it})*(l_1 * P_{i,\max} + l_2 * P_{i,\min} + l_3 * R^s_{S,it}) \tag{31}$$

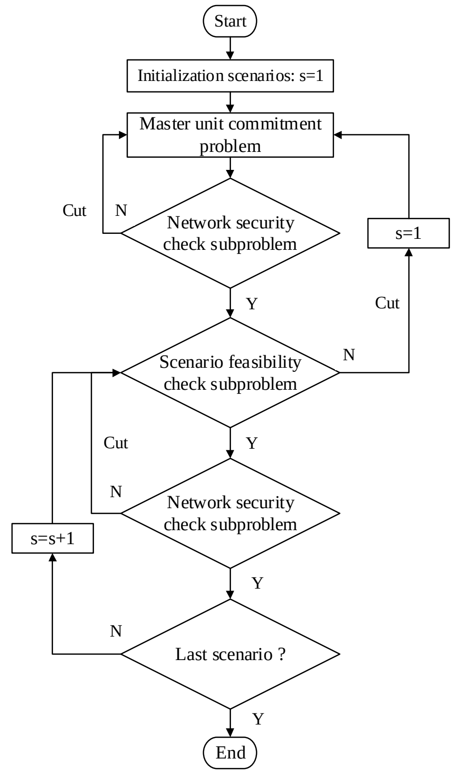

Fig. 3 The flowchart of the Benders algorithm

Case Study

A modified IEEE 118-bus test system is used to make simulation and verification. The system has 54 thermal units, one wind farm. The wind farm is located at bus 12, whose installed capacity is 300MW. The cut-in wind speed of the wind turbine is 3.5 m/s, the rated wind speed is 12 m/s, and cut-out speed is 20 m/s. The forecast wind speed curve is shown in Fig. 4, and the red bold solid curve in Figure 5 shows the wind power output.

Based on the established wind power irregular distribution, 500 wind scenarios were randomly generated by Monte Carlo method, and 10 typical wind scenarios were retained by backward retraction techniques, as 10 blue dashed curves shown in Fig .5.

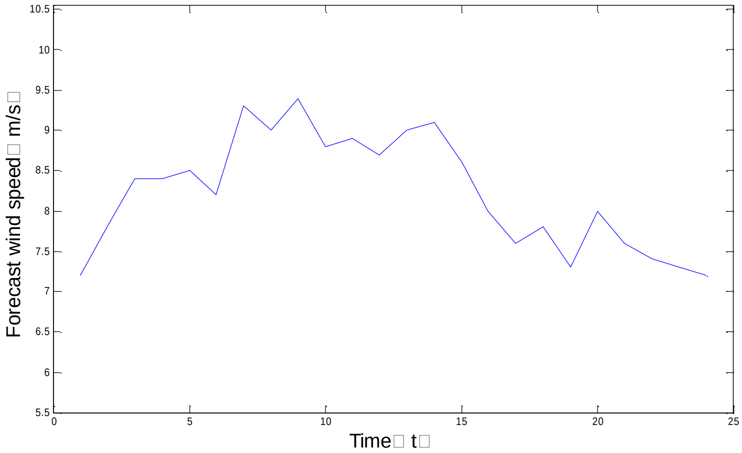

Fig. 4 Forecast curve of wind speed

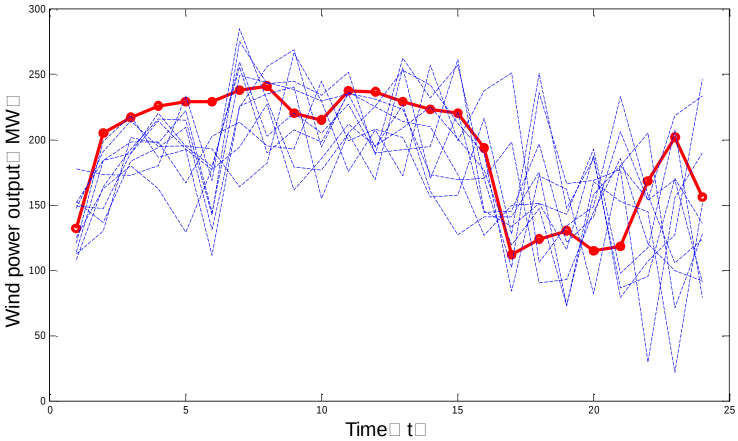

Fig. 5 Calculation scenarios of wind power

The wind power forecasting output and the wind power calculation scenarios are taken as the input data to solve deterministic unit commitment and probabilistic unit commitment under the same simulation conditions, respectively. The results are shown in Table 1.

Table 1 Comparison of two kinds of unit commitment solutions

Indexes of solution	deterministic unit commitment	probabilistic unit commitment
Operation cost [$]	920972	921436
Number of iteration	0	9
Time of solving [second]	5.12	480.772

As shown in Table 1, the deterministic unit commitment only considers the wind power forecasting output and does not consider wind error scenarios directly, so the scene check and iteration number are always zero. Compared with deterministic unit commitment, the probabilistic unit commitment cost is slightly higher, because the master problem solutions in probabilistic unit commitment model would be checked and guarantee that all the 10 calculation scenarios can be satisfied by units output adjustment. 9 iterations occur in probabilistic unit commitment, which means that 9 Benders are added to master problem, so the feasible solution narrowed and the cost increased.

Based on irregular distribution of wind power and Monte Carlo scenarios sampling, 500 wind power scenarios are regenerated to conduct scenarios check for two kinds of unit commitment solutions under the same condition. If the solution can't cope with wind fluctuation by unit output adjustment, the wind power curtailment will occur, which means that the unit commitment solution fails in this wind power scenario. On the contrary, the solution is feasible in the scene. Simulation results are shown in Table 2.

Table 2 Comparison of two kinds of unit commitment solutions checked in 500 scenarios

Indexes of solution	deterministic unit commitment	probabilistic unit commitment
Number of passed scenarios	407	455
Rate of passed scenarios	81.4%	91%
Wind power curtailment[MW]	1605.967	365.2292

As Table 2 shows, 10 groups of typical wind power computing scenarios are considered in the probabilistic unit commitment model, so the scenario verification pass rate is higher than deterministic unit commitment. Wind power curtailment in the probabilistic unit commitment is obviously less than deterministic unit commitment, which means that the probabilistic unit commitment is more capable of coping with wind power fluctuation.

Conclusions

In the paper, the deterministic unit commitment and the probabilistic unit commitment were compared in detail from the essence of the model, the scheduling cost and the solution efficiency. The results in Table 1 point out that, deterministic unit commitment has an advantage over probabilistic unit commitment in system operation cost and solving efficiency, which can be handled fairly easily with the rapid development of the computer. In addition, the iterations of the probabilistic unit commitment between the master problems and two subproblems are the essence of considering wind power fluctuation. The checked results of two kinds of unit commitment solutions in 500 wind power error scenarios, show that the scenario-based probabilistic unit commitment has advantage of coping with wind power fluctuation. The comparison results provide strong technical support for the engineering community to accept the operation of probabilistic unit commitment.

Acknowledgements

This work was financially supported by the National Natural Science Foundation (No. 51177019 and No. 51577031) and State Grid Corporation of China (Research of the Key Technique for Large-scale New Energy Integration Dispatching Plan and Security Correction based on Probability Analysis, 8508000149).

References

[1] Yao YAO, Jilai YU. Multi-objective Hybrid Optimal Dispatch of Power System Considering Reserve Risk Due to Wind Power[J]. Automation of Electric Power Systems, 2011, 35(22): 118-124. “In Chinese”.

[2] Haiyan CHEN, Jinfu CHEN, Xianzhong DUAN. Fuzzzy Modeling and Optimization Algorithm on Dynamic Economic Dispatch in Wind Power Integered System[J]. Automation of Electric Power Systems, 2006, 30(2): 22-26. “In Chinese”.

[3] Guoqiang ZHANG, Boming ZHANG. Optimal Power Flow Approach Considering Secondary Reserve Demand with Wind Power Integration[J]. Automation of Electric Power Systems, 2009, 33(8): 25-28. “In Chinese”.

[4] Wei ZHOU, et al. Dynamic Economic Dispatch in Wind Power Integrated System[J]. Proceedings of the CSEE, 2009, 29(25): 13-18. “In Chinese”.

[5] Wen JIANG, Zheng YAN. Dynamic economic dispatch considering wind power penetration based on IPSO[J]. Power System Protection and Control, 2010, 38(21): 173-178. “In Chinese”.

[6] Yu LEI, Ming YANG, Xushan HAN. A two-stage stochastic optimization of unit commitment considering wind power based on scenario analysis[J]. Power System Protection and Control, 2012, 40(23): 58-67. “In Chinese”.

[7] Wenmeng ZHAO, Mingbo LIU. A Dynamic Reduction Based Multi-cut Method for Solving Stochastic Unit Comitment with Wind Farm Integration[J]. Automation of Electric Power Systems, 2014, 38(9): 26-32. “In Chinese”.

[8] Hodge B M , Lew D , Milligan M , et al . Wind power forecasting error distributions: an international comparison [C]//Proceedings of the 11th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants Conference . Lisbon Portugal: NREL, 2012 .

[9] Woong Ko , Don Hur , Jong-Keun Park. Correction of wind power forecasting by considering wind speed forecast error[J]. Journal of International Council on Electrical Engineering, Vol. 5, Issue. 1, 2015, pages: 47-50.

[10] Fang LIU, Yi PAN et al. Piecewise Exponential Distribution Model of Wind Power Forecasting Error[J]. Automation of Electric Power Systems, 2013, 18: 14-19. “In Chinese”.

[11] Guojun XIAO, Renun ZHOU, Suping WU. Security Economic Dispatch in Wind Power Integrated Systems Using an Interactive Decision Making Method[J]. Electrical Engineering, 2013, 04: 1-5+10. “In Chinese”.

[12] Haiyan CHEN, Jinfu CHEN, Xianzhong DUAN. Fuzzy Modeling and Optimization Algorithm on Dynamic Economic Dispatch in Wind Power Integrated System[J]. Automation of Electric Power Systems, 2006, 02: 22-26. “In Chinese”.

[13] Wang J, Shahidehpour M, Li Z. Security-constrained unit commitment with volatile wind power generation[J]. IEEE Transactions on Power Systems, 2008, 23(3): 1319-1327.