On Spinning Reserve Determination and Power Generation Dispatch Optimization for Wind Power Integration Systems

Shu Xia, Ming Zhou, *IEEE member*, Gengyin Li, *IEEE member*, Yang Liu, and Meng Xiang

***Abstract*--A joint optimization dispatching model of active power and AGC for wind power integration systems is proposed. In the mathematical model, both the probabilistic distributions of load and wind forecast errors are introduced to deal with the uncertainties. To make the optimization results more rational, an approach on spinning reserve determination for wind power integration systems is presented based on a given risk level. To describe the operation state more accurately, a method of multi-scenario is adopted and the actual output of AGC generators will be adjusted according to the AGC unit modification strategy in each scenario. The case studies are carried out on a system with 10 AGC units and a wind farm. Compared to conventional dispatch method, the results show that the proposed optimization model is rational.**

***Index Terms*-- wind power, AGC, joint optimization, spinning reserve, multi-objective optimization**

I. Introduction

GENERATION dispatch has important economy significance, which ensures power balance and frequency stability, and plays an irreplaceably role in power system operation [1]. In recently years, wind power penetration into power systems is rapidly increasing. Since wind energy is a kind of fluctuating, random and uncontrollable resource, so wind power is difficult to accurately predict and dispatch [2-3]. In order to ensure reliable and economic operation of power systems with wind power, the randomness of wind power should be taken into account in scheduling generation for the wind power integration systems.

The problem of power generation dispatch for thermal-wind power systems has attracted wide attention. In [4], up spinning reserve and down spinning reserve are introduced to deal with the impacts of wind power prediction error on the dispatch. In [5], factors for overestimation and underestimation of available wind energy are considered in the model which could adapt random wind power output better. In [6], the two-parameter Weibull distribution is adopted to describe wind speed, and the probability of stochastic wind power is included in the constraint set. In [7], a multi-objective optimization model is proposed by considering the cost factors and environmental factors based on Ref. [4]. In the above literatures, the research on wind power randomness has made some progress, but how to determine and schedule the additional spinning reserve requirement due to wind power fluctuation, especially how to jointly dispatch spinning reserve with power generation, is little to be concerned.

In practice, generation dispatch is fulfilled by a computer program, which is run periodically, usually every 5 or 10min in ahead, to give units' outputs (as the set points of unit control at the start of each dispatch period) according to the predicted load and wind power, and units' characteristics. During the duration of 5 or 10min, the differences between the predicted values and the actual values of wind power and load are filled by AGC units [8-9]. Therefore, it can be seen that generation dispatch determines the scheduled units' outputs at the beginning of every dispatch period. Among all scheduled units, some of them are then operating at the scheduled outputs, which have no capability for further adjustment, the other units, called AGC units, the dispatched outputs are used as the base outputs of AGC units, in the same time, the AGC units remain capacity to pick up power imbalance possibly emerging during the duration, or in other words, to act as providing spinning reserve. Increasing wind power penetration requires additional spinning reserve demand, which accordingly increases the demand to AGC capacity, so how to determine the spinning reserve requirement, and how to dispatch this spinning reserve in an economical way is a critical problem. At the same time, the gap of actual outputs and base outputs of AGC units become larger because of wind forecasting error. The actual output of AGC unit may deviate from the economic point seriously. Thus, the change of AGC unit output should be taken into account in active power dispatch.

In this paper, on the base of conventional generation dispatch model, the uncertainties of load and wind power are modeled in a joint probability form. Then an approach on spinning reserve determination for wind power integration systems is presented based on a given risk level. A joint optimization approach on generation dispatch incorporating with spinning reserve dispatch among AGC units is proposed.

The work is funded by National Natural Science Foundation of China (51177043). The authors are with State Key Laboratory for Alternate Electrical Power System with Renewable Energy Sources(North China Electric Power University), Beijing 102206, P.R.China (e-mail: 870828@ncepu.edu.cn; zhouming@ncepu.edu.cn; ligy@ncepu.edu.cn; ly19890830@ncepu.edu.cn; xiangmeng1206@126.com).

978-1-4673-2729-9/12/$31.00 ©2012 IEEE

Multiple scenarios are adopted to simulate the fluctuation of wind power and load. The actual output of AGC generators are adjusted according to the AGC unit modification strategy in each scenario. The numerical examples are done to test the proposed approach, and the comparison with a conventional dispatch method is given.

II. Conventional Generation Dispatch Model without Wind power

A. Objective Function

Power generation dispatch is a nonlinear optimization problem, and it is common to take the total fuel cost as the optimization objective [10]. Considering the valve-point effect, the total fuel cost can be expressed as

$$C=\sum_{i=1}^{N}\left[a_i+b_iP_i+c_iP_i^2+\left|d_i\sin\{e_i(P_{i\min}-P_i)\}\right|\right] \tag{1}$$

where C is the fuel cost, N is the number of generators in the system, P_i and $P_{i\min}$ is the power output and the lower generation limit of the ith generator, respectively, a_i, b_i, c_i, d_i, e_i are the cost coefficients of the ith generator.

B. Constraints

If power loss is not taken into account, the constraints of generation dispatch include power balance constraint, reserve constraint and generators output constraint.

i) Power balance constraint

$$\sum_{i=1}^{N}P_i-P_L=0 \tag{2}$$

ii) Reserve constraint

$$\sum_{i=1}^{N}(P_{i\max}-P_i)\ge P_R \tag{3}$$

iii) Generators output constraint

$$P_{i\min}\le P_i\le P_{i\max} \tag{4}$$

where P_L is load demand, P_R is the total reserve requirement, $P_{i\max}$ is the upper generation limit of the ith generator.

III. Spinning Reserve Determination

A. Modeling Uncertainties of Load and Wind Power

In the conventional power dispatch model, the main uncertainty is load, which can be expressed in the form of load forecast error. Considering the load prediction error, the actual load P_L can be expressed as [11]

$$P_L=\bar{P}_L+\Delta P_L \tag{5}$$

where $\bar{P}_L$ is the predicted load, ΔP_L is the prediction error, which is generally considered as a normally distributed variable with the mean of 0 and the standard deviation of σ_L.

In a wind-thermal power system, the uncertainties come from both load and wind power. Same as load forecast, wind power is got through forecasting wind speed, then transforming to power.

Suppose the actual wind speed v is expressed as [12]

$$v=\bar{v}+\Delta v \tag{6}$$

where $\bar{v}$ is the predicted wind speed, Δv is the predict error which can be considered as normal distribution with the mean of 0 and the standard deviation of σ_v. The probability density function $f_v()$, and probability distribution function $F_v()$ of wind speed can be expressed as

$$f_v(v)=\frac{1}{\sqrt{2\pi}\sigma_v}e^{-\frac{(v-\bar{v})^2}{2\sigma_v^2}} \tag{7}$$

$$F_v(v)=\Phi\left(\frac{v-\bar{v}}{\sigma_v}\right) \tag{8}$$

Power output of a wind farm is determined by wind speed, types of wind turbines, the number of wind turbines, and wind turbines arrangement. In this paper, the following wind power output model of a wind farm is adopted [6]:

$$P_W=N_W p_w=\begin{cases}0, & 0\le v<v_{in}\ \ or\ \ v>v_{out}\\ \dfrac{(v-v_{in})N_W p_r}{v_r-v_{in}}, & v_{in}\le v<v_r\\ N_W p_r, & v_r<v\le v_{out}\end{cases} \tag{9}$$

where P_W is the output of a wind farm, p_w is the output of a single wind turbine, N_W is the number of wind turbines, p_r is the rated power of a wind turbine generator, v_{in}, v_r, v_{out} is the cut-in, the rated and the cut-out wind speed, respectively. The probability of the event P_W=0 and the event P_W=N_Wp_r is calculated by

$$\begin{aligned}P_{rob}\{P_W=0\}&=F_v(v_{in})+1-F_v(v_{out})\\&=1-\Phi\left(\frac{v_{out}-\bar{v}}{\sigma_v}\right)+\Phi\left(\frac{v_{in}-\bar{v}}{\sigma_v}\right)\end{aligned} \tag{10}$$

$$\begin{aligned}P_{rob}\{P_W=N_W p_r\}&=F_v(v_{out})-F_v(v_r)\\&=\Phi\left(\frac{v_{out}-\bar{v}}{\sigma_v}\right)-\Phi\left(\frac{v_r-\bar{v}}{\sigma_v}\right)\end{aligned} \tag{11}$$

where $P_{rob}\{\cdot\}$ is the probability of the occurrence of the event in the brackets. The mean output of a wind farm and its standard deviation are computed by

$$\bar{P}_W=\left(\frac{\bar{v}-v_{in}}{v_r-v_{in}}\right)N_W p_r \tag{12}$$

$$\sigma_W=\frac{N_W p_r\sigma_v}{v_r-v_{in}} \tag{13}$$

When $0<P_W<N_Wp_r$, the probability density function $f_W(.)$ of wind farm output is

$$f_W(P_W)=\frac{1}{\sqrt{2\pi}\sigma_W}e^{-\frac{(P_W-\bar{P}_W)^2}{2\sigma_W^2}} \tag{14}$$

According to Eq. (10) to Eq. (14), the probability distribution function of wind farm output is

$$F_W(P_W)=\begin{cases}0, & P_W<0\\ 1-\Phi\left(\dfrac{v_{out}-\bar{v}}{\sigma_v}\right)+\Phi\left(\dfrac{P_W-\bar{P}_W}{\sigma_W}\right), & 0\le P_W<N_W p_r\\ 1, & P_W\ge N_W p_r\end{cases} \tag{15}$$

By comprehensive consideration of load prediction error and wind power prediction error, an equivalent power P_Z is defined as

$$P_Z = P_W - \Delta P_L \tag{16}$$

And the joint probability density function of P_Z is calculated by Eq. (17).

$$f_Z(P_Z) = P_{rob}\{P_W = 0\} f_L(P_Z) + P_{rob}\{P_W = N_W p_r\} f_L(P_Z - N_W p_r) + \frac{1}{\sqrt{2\pi}(\sqrt{\sigma_L^2 + \sigma_W^2})} e^{-\frac{(P_Z - \bar{P}_W)^2}{2(\sqrt{\sigma_L^2+\sigma_W^2})^2}} \times \left[\Phi\left(\frac{N_W p_r - \frac{\sigma_L^2 \bar{P}_W + \sigma_W^2 P_Z}{\sigma_L^2 + \sigma_W^2}}{\frac{\sigma_L \sigma_W}{\sqrt{\sigma_L^2 + \sigma_W^2}}} \right) - \Phi\left(\frac{-\frac{\sigma_L^2 \bar{P}_W + \sigma_W^2 P_Z}{\sigma_L^2 + \sigma_W^2}}{\frac{\sigma_L \sigma_W}{\sqrt{\sigma_L^2 + \sigma_W^2}}} \right) \right] \tag{17}$$

where $f_L(.)$ is the probability density function of load prediction error. The probability distribution function of P_Z is

$$F_Z(P_Z) = \int_{-\infty}^{P_z} f_Z(t)dt \tag{18}$$

B. Up and Down Spinning Reserve Determination

In a wind power integration system, due to wind power fluctuation and the difficulty to accurately predict wind power, it is necessary for the system to prepare more up spinning reserve, denoted by P_R^u, and down spinning reserve, denoted by P_R^d. P_R^u is used to fill power deficit when wind power output is lower than the predicted value. P_R^d is preserved to accommodate wind power in the maximum extend. When wind power penetration ratio is low, the system could accommodate all wind power, but with the increase of wind power penetration, the system may be difficult to accommodate all wind power due to the limit of available spinning reserve. The scheduling mode to wind power is as follows:

1) When down spinning reserve is enough, all wind power is dispatched firstly.

2) When down spinning reserve is insufficient, part of the wind power is abandoned according to P_R^d [13].

Comprehensively considering the compromise between reliability and economy, we assume that P_R^u and P_R^d are determined under a certain level of risk, that is P_R^u and P_R^d to meet a certain confidence level, which is defined by

$$P_{rob}\left\{P_R^u \geq P_{WA} - P_Z\right\} = \beta_1 \tag{19}$$

$$P_{rob}\left\{P_R^d \geq P_Z - P_{WA}\right\} = \beta_2 \tag{20}$$

where P_{WA} is the output of wind farm to be scheduled, β_1 and β_2 is the confidence level corresponding to up reserve and down reserve, respectively.

According to Eq. (18) to Eq. (20), we can get Eq. (21) and Eq. (22).

$$F_Z\left(P_{WA} - P_R^u\right) = P_{rob}\left\{P_Z \leq P_{WA} - P_R^u\right\} = 1 - \beta_1 \tag{21}$$

$$F_Z\left(P_{WA} + P_R^d\right) = P_{rob}\left\{P_Z \leq P_{WA} + P_R^d\right\} = \beta_2 \tag{22}$$

$F_Z(.)$ is a monotonically rising function, so Eq. (21) and Eq. (22) can be solved by using dichotomy method. As a result, Eq. (21) and Eq. (22) becomes

$$P_{WA} - P_R^u = F_Z^{-1}(1 - \beta_1) \tag{23}$$

$$P_{WA} + P_R^d = F_Z^{-1}(\beta_2) \tag{24}$$

Formula (23) and (24) set up the relationship of spinning reserve and confidence level and the scheduled wind power. Base on the above statistical analysis to fluctuating wind power and load, given a pair of β_1 and β_2, there are 3 variables, P_R^u, P_R^d and P_{WA}, but only two equations, so we cannot solve out P_R^u or P_R^d. One variable is required to fix. In [7], the wind power forecast value is assigned to P_{WA}, this kind of arrangement may result in unreasonable spinning reserve demand. In Eq. [11], the scheduled outputs of wind farms are set as optimization variables, and up and down spinning reserve are added into the objective function as a cost index. However, this method will increase the complexity of optimization problem, and when the wind farms and other generators belong to the same group, the method is difficult to apply. In this paper, the output of wind farms is determined according to available up and down spinning reserve. Assume there is proportional relationship between up and down spinning reserve, that is

$$\frac{P_R^u}{P_R^d} = k \tag{25}$$

where k is the correlation coefficient of up and down spinning reserve. According to Eq. (23) to Eq. (25), the scheduled output of wind farms and total reserve capability can be got by

$$P_{WA} = \frac{F_Z^{-1}(1 - \beta_1) + kF_Z^{-1}(\beta_2)}{1 + k} \tag{26}$$

$$P_R^u = \frac{k[F_Z^{-1}(\beta_2) - F_Z^{-1}(1 - \beta_1)]}{1 + k} \tag{27}$$

$$P_R^d = \frac{F_Z^{-1}(\beta_2) - F_Z^{-1}(1 - \beta_1)}{1 + k} \tag{28}$$

C. Spinning Reserve Allocation among AGC Units

The differences between the predicted values and the actual values of wind power and load are filled by AGC units. Thus, AGC units are acting as providing the spinning reserve which aims to cover the forecast error of wind speed and load. Assume the number of AGC units under real-time control is N_G, and the ith AGC generator provides the amount of up and down regulation capacity, P_i^+ and P_i^-. The up and down spinning reserve constraints can be defined as

$$\sum_{i=1}^{N_G} P_i^+ \geq P_R^u \tag{29}$$

$$\sum_{i=1}^{N_G} P_i^- \geq P_R^d \tag{30}$$

$$P_{i\min}^+ \leq P_i^+ \leq \min[P_{i\max}^+, (P_{i\max} - P_i)] \tag{31}$$

$$P_{i\min}^- \leq P_i^- \leq \min[P_{i\max}^-, (P_i - P_{i\min})] \tag{32}$$

where $P_{i\min}^+$, $P_{i\max}^+$ are the minimum and maximum up regulation capacity of ith AGC unit, $P_{i\min}^-$ $P_{i\max}^-$ are the minimum and maximum down regulation capacity of the ith AGC unit. Eq. (29) and Eq. (30) will ensure rational use of the up and down regulation capacity.

IV. Joint Optimization Model for Active Power and AGC

A. Multiple scenarios division

In the above Section III, the equivalent power P_Z and its probability distribution has got, but it is a continuous stochastic variable, it is difficult to apply directly into the dispatch, so we take multi-scenario method to represent this continuous process. Figure 1 shows the probability density curve of stochastic equivalent power value P_Z. Given a pair of confidence level β_1 and β_2, the possible variation range of P_Z to be considered in the dispatch is [$P_{WA} - P_R^u$, $P_{WA} + P_R^d$]. This range is then divided into L intervals with the same range by using the method of discretization. The two ends of the lth interval are P_l^Z and P_{l+1}^Z , and each interval corresponds to a scene. Then the probability value p_l and expectations P_{El} of the l-th interval are defined as

$$p_l = \int_{P_l^Z}^{P_{l+1}^Z} f_Z(P_Z) dP_Z \tag{33}$$

$$P_{El} = \frac{\int_{P_l^Z}^{P_{l+1}^Z} [f_Z(P_Z) P_Z] dP_Z}{p_l} \tag{34}$$

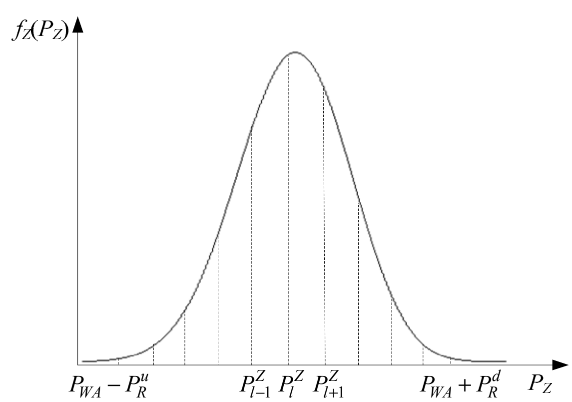

Fig. 1. Sketch map of discretization of stochastic equivalent power P_Z

B. AGC unit modification strategy

The deviation between the predicting value and the actual value of wind power and load are adjusted by AGC units mainly. Thus, the actual outputs of AGC units may be different from the scheduled outputs. In order to make optimization results more accurately, the actual output of units should be applied in the calculation of fuel cost. In each scenario, the actual outputs of AGC units can be determined according to the modification strategy.

There are some methods modifying AGC units' output. This paper adopts the modification strategy given by Ref. [14]. Without considering the network constraints, the outputs of AGC units can be amended as follows:

Step 1: Calculate the load extraction factor k_i of the ith AGC unit, which formally as

$$k_i = \frac{P_i}{P_L} \tag{35}$$

where P_i is the base point of the ith AGC unit output;

Step 2: According to the scheduled value P_{WA} and actual value P_{ZA} of the equivalent power, the deviation between them can be described as $\Delta P_G = P_{WA} - P_{ZF}$;

Step 3: Calculate the adjustable amount ΔP_{Gi} of the ith AGC unit, which can be expressed as

$$\Delta P_{Gi} = \frac{k_i \Delta P_G}{\sum_{i=1}^{N_G} k_i} \tag{36}$$

where

$$\begin{cases} \Delta P_{Gi} \leq P_i^+, & \Delta P_G \geq 0 \\ -\Delta P_{Gi} \leq P_i^-, & \Delta P_G < 0 \end{cases} \tag{37}$$

Step 4: Check whether all the AGC units satisfy Eq.(37). If satisfied, stop the calculation and output results. If not satisfied, AGC units which beyond limits are grouped as a set, namely A, and AGC units which still has spare regulation capacity are grouped as a set, namely B. Then modify the adjustable amount of the units in set A and set B, respectively, the adjustment methods are

$$\Delta P_{Gn}^C = \begin{cases} P_n^+, & \Delta P_{Gn} \geq P_n^+ \ and \ \Delta P_{Gn} \geq 0 \\ -P_n^-, & -\Delta P_{Gn} \geq P_n^- \ and \ \Delta P_{Gn} < 0 \end{cases}, n \in A \tag{38}$$

$$\Delta P_{Gm}^C = \Delta P_{Gm} + \frac{k_m \sum_{n \in A} (\Delta P_{Gn} - \Delta P_{Gn}^C)}{\sum_{j \in B} k_j}, m \in B \tag{39}$$

where ΔP_{Gn}^C is the adjustable amount of the nth AGC unit after checking.

Step 5: Go to step 4.

From Eq. (37), it can be seen that the actual output of AGC is not only related to its base point, but also to its regulation capacity P_i^+ or P_i^- . Therefore, how to rationally assign the regulation capacity of AGC units is a problem. To solve this problem, the regulation capacity of AGC unit is taken as decision variable in the joint optimization with the base points of all generators.

C. Objective Function

At each scenario, the actual output of AGC unit is adjusted, which is a stochastic variable. Thus, Eq. (1) is changed into

$$C = \frac{\sum_{l=1}^{L}(p_l C_l)}{\sum_{l=1}^{L} p_l} \quad (40)$$

where C_l are the fuel cost at the lth scenario.

D. Constraints

In the joint dispatch model for active power and AGC output, the constraints include power balance constraint shown in Eq.(41), reserve constraints shown in Eq. (29) and Eq. (30), and generator output constraints same as Eq. (4).

$$\sum_{i=1}^{N} P_{i,l} + P_{El} - \overline{P_L} = 0, \quad l = 1,2,...,L \quad (41)$$

where $P_{i,l}$ is the actual output of the ith generator in the lth scenario, $\overline{P_L}$ is the predicted load.

V. Numerical Examples

To verify the effectiveness of the proposed method, a system with 10 AGC units [10] and a wind farm is tested. The parameters of AGC units are given in Table I. There are 100 wind turbine generators in the wind farm, and the rated power of each wind turbine generator is 2MW. The parameters of wind turbine are: the cut-in wind speed v_{in}=4m/s, the rated wind speed v_r=12m/s, and the cut-out wind speed v_{out}=20m/s. The predicted load is 2000MW, and the standard deviation of load prediction error is 2% of the prediction value. The standard deviation of wind speed prediction error is 10% of the prediction value. The correlation coefficient of up and down spinning reserve k=1. When the predicted wind speed $\overline{v}$ are 6m/s, 8m/s, 10m/s and 12m/s, respectively. The relationship between scheduled output of wind farm and confidence level is shown in Fig. 2, and the relationship between total up/down spinning reserve and confidence level is shown in Fig.3.

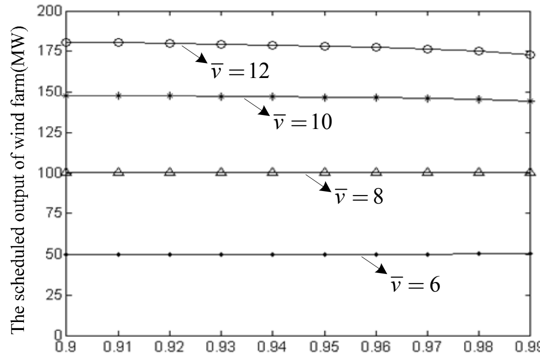

Fig. 2. The relationship between scheduled wind power output and confidence levels β_1 and β_2

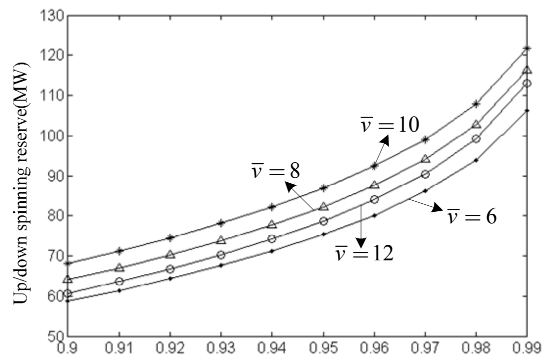

Fig. 3. The relationship between up/down spinning reserve demands and confidence levels β_1 and β_2

TABLE I
The Parameters of AGC Units

Unit	$P_{i\min}$(MW)	$P_{i\max}$(MW)	a_i($/h)	b_i($/MWh)	c_i($/(MW)^{2}h)	d_i($/h)	e_i(rad/MW)	$P^+_{\max}/P^-_{\max}$(MW)	$P^+_{\min}/P^-_{\min}$(MW)
1	10	55	1000.403	40.5407	0.12951	33	0.0174	10	4
2	20	80	950.606	39.5804	0.10908	25	0.0178	10	4
3	47	120	900.705	36.5104	0.12511	32	0.0162	20	8
4	20	130	800.705	39.5104	0.12111	30	0.0168	20	8
5	50	160	756.799	38.5390	0.15247	30	0.0148	20	8
6	70	240	451.325	46.1592	0.10587	20	0.0163	30	12
7	60	300	1243.531	38.3055	0.03546	20	0.0152	40	16
8	70	340	1049.998	40.3965	0.02803	30	0.0128	40	16
9	135	470	1658.569	36.3278	0.02111	60	0.0136	50	20
10	150	470	1356.659	38.2704	0.01799	40	0.0141	50	20

From Fig.2, it can be seen that the scheduled output of wind farm is different from the predicted wind power. When $\overline{v} = 8$ m/s, the scheduled output of wind power is similar to the prediction value, which is 100MW. When $\overline{v} = 6$ m/s, the scheduled output of wind power is slightly larger than the predicting output, and with the confidence level increasing, the scheduled output of wind power becomes greater. When $\overline{v} = 10$ m/s or $\overline{v} = 12$ m/s, the scheduled output of wind power is slightly fewer than the predicting output, and with the confidence level increasing, the scheduled output of wind farm becomes smaller. Thus, the scheduled output of wind power is related to the confidence level and wind speed. As can be seen from Figure 3, for a given wind speed predicting value, with the confidence level increasing, the up and down spinning reserve the system will also increase. When $\overline{v}$ = 6m/s, 8m/s and 10m/s, for the same confidence level, with the predicting value of wind speed increasing, the up and down spinning reserve will also increase. When $\overline{v}$ increases to 12m/s, the output of wind power is limited by rated power capacity, therefore, the up and down spinning reserve is fewer than the event when $\overline{v}$ =10m/s .

TABLE II
THE SELECTED RESULTS OF UNITS IN DIFFERENT OBJECTIVES

Unit	Conventional dispatch model	Joint dispatch model	
	Base point of output (MW)	Up/down regulation capacity (MW)	Base point of output (MW)
1	55	0	55
2	73.0860	6.0052	73.9856
3	75.2000	9.7189	76.5358
4	65.8402	19.96	66.9045
5	55.1060	0	55.6948
6	70	0	70
7	250.7110	28.0581	253.1866
8	281.0098	38.0305	284.4907
9	454.0470	20.0009	449.9606
10	470	0	470
Wind farm	150	--	144.2474

TABLE III
Fuel cost in different scenarios by different model

Scene	Fuel Cost ($)	
	Conventional dispatch mode	Joint dispatch model
1	104081.1177	104035.3975
2	102674.3706	102643.9080
3	101289.8263	101269.3273
4	99920.4504	99913.9242
5	98567.5314	98567.2766
6	97227.7374	97228.6252
7	95901.9092	95898.9175
8	94590.9149	94578.7222
9	93295.1441	93270.7067
10	92015.1023	91977.9837

The parameters of system are set as: β_1=β_2=0.99, k=1. When $\overline{v}$ =10m/s, the scheduled output value of wind farm is 144.2474MW, both the up and down spinning reserve capacity are 121.7743MW. Thus the range of P_Z is [22.4731MW， 266.0217MW]. P_Z is divided into 10 segments. Differential evolution (DE) [15] is adopted to solve the joint dispatch model. The parameters of the DE are set as: the population size is 100, the largest number of iterations is 300, the mutation factor is 0.4, the crossover factor C_R is 0.5. The dispatch result is shown in TABLE II and the expected value of fuel cost is 97681.8695$. To compare the proposed model with conventional active power dispatch model [7, 10], a simulation is conducted. When $\overline{v}$ =10m/s, the result of conventional generation dispatch model is also shown in TABLE II. The result of conventional generate dispatch model is texted in the power dispatch considering the change of AGC unit output, and the expected value of fuel cost is 97692.0190$ which is 10.1495$ higher than the result of joint optimization model. The fuel cost in different scenarios by the result of conventional dispatch model and by the result of joint dispatch model is shown in TABLE III. From TABLE III, it can be seen that the gap of fuel cost in different scenarios is large. This is because the actual output of AGC units is adjusted in each scene. Except scene 6, the fuel cost of conventional dispatch model is higher than joint dispatch model.

VI. CONCLUSIONS

Considering generation dispatch and AGC reserve assigning, a joint optimization model for active power and AGC is established. An example of 10 units system containing a wind farm is analyzed, and the conclusions are as follows:

1) According to the normal distribution of load and wind speed prediction error, a stochastic equivalent power is formed, which can describe the uncertainty of load and wind speed well.

2) The scheduled output of wind power is related to some factors, such as the confidence level, wind speed, up and down spinning reserve. Thus, in the practical dispatch, the scheduled output of wind power should be arranged according to these factors.

3) Several scenes are set up by discrete method, and then the outputs of AGC generators are adjusted according to modification strategy in different scenarios, which can describe the operation state more accurately.

4) Compared to the conventional dispatch method, the joint optimization model can bring better economic benefits.

In the future, unit forced outage and network constraints will be further considered in the model.

VII. REFERENCES

[1] B. Zhang, W. C. Wu and T. Y. Zhang, "Design of a multi-time scale coordinated active power dispatching system for accommodating large scale wind power penetration, " *Automation of Electric Power Systems*, vol.35, no. 1,pp.1-6, Jan. 2011.

[2] X. Y. Yang, Y. Xiao and S. Y. Cheng, "Wind speed and generated power forecasting in wind farm, "*Proceeding of the CSEE*, vol. 25, no. 11, pp. 1-5, Jun. 2005.

[3] T. Ackermann, "Wind power in power system," London, UK: John Wiley & Sons, Oct. 2005.

[4] T. Y. Lee, "Optimal spinning reserve for a wind-thermal power system using PSO," *IEEE Trans. on Power Systems*, vol. 22, no. 4, pp. 1612-1621, Nov. 2007.

[5] H. John, C. Y. David and B. Kalu, "An economic dispatch model incorporating wind power, "*IEEE Trans. on Energy Conversion*, vol. 32,no. 2, pp. 603-611, Jun. 2008.

[6] L. Xian and X. Wilsun, "Economic load dispatch constrained by wind power availability: a here-and-now approach," *IEEE Trans. on Sustainable Energy*, vol. 1, no. 1, pp. 2-9, Apr. 2010.

[7] J. C. Lee, W. M. Lin and G. C. Liao, "Quantum genetic algorithm for dynamic economic dispatch with valve-point effects and including wind power system," *Electrical Power and Energy Systems*, vol. 33, no. 2, pp. 189-197, Feb. 2011.

[8] Z. H. Gao, X. L. Teng and C. B. Zhang, "Solution of active power dispatch and control scheme for interconnected power grids with large-scale wind power integration, " *Automation of Electric Power Systems*, vol. 34, no. 17, pp. 37-41, Sep. 2010.
[9] Y. C. Zhou, Y. Li and B. B. Wang, "Impact of two dispatching methods on AGC unit dispatch in electricity market environment, " *Power System Technology*， vol. 34, no. 7, pp.154-159, Jul. 2010.
[10] M. Basu, "Economic environmental dispatch using multi-objective differential evolution," *Applied Soft Comptuing*, vol. 11, no. 2, pp. 2845-2853, Mar. 2011.
[11] W. Zhou, Y. Peng and H. Sun, "Optimal wind-thermal coordination dispatch based on risk reserve constraints," *European Transactions on Electrical power*, vol. 21, no. 1, pp. 740-756, Jul. 2011.
[12] M. Lange, "On the uncertainty of wind power predictions-analysis of the forecast accuracy and statistical distribution of errors," *Journal of Solar Energy Engineering*, vol. 127, no. 2, pp. 177-184, May. 2005.
[13] C. L. Chen, "Optimal wind-thermal generating unit commitment, "*IEEE Trans. on Energy Conversion*, vol. 23,no. 1, pp. 273-208, May. 2008.
[14] N. Chen and J. L. Yu, "Active power dispatch and regulation of wind power system based on electrical dissecting information of electric power network, " *Proceeding of the CSEE*, vol. 28, no. 16, pp. 51-58, Jun. 2008.
[15] J. P. Chiou, "A variable scaling hybrid differential evolution for solving large-scale power dispatch problems, " *IET Gener., Transm.. & Distrib.*, vol. 3, no. 2, pp. 154-163, 2009.

VIII. Biographies

Shu Xia was born in Anhui Province, China. He received the B.S. and M.S. degrees in Electrical Engineering from North China Electricity Power University (NCEPU) in 2008 and 2010, respectively. Currently, he is perusing a Ph.D. degree in NCEPU and his research interest is power system analysis and control.

Ming Zhou (M’06) was born in Hubei Province, China. She received the B.S., M.S. and Ph.D. degrees in Electrical Engineering from North China Electricity Power University (NCEPU) in 1989, 1992, and 2006, respectively. Since 1992, Dr. Zhou has been with the School of Electrical and Electronic Engineering at NCEPU, where she is currently a professor. Her areas of interest include power systems economics, power system analysis and reliability, and power quality analysis.

Gengyin Li (M’03) was born in Hebei Province, China. He received the B.S., M.S. and Ph.D. degrees, all in Electrical Engineering from North China Electricity Power University (NCEPU) in 1984, 1987, and 1996, respectively. Since 1987, Dr. Li has been with the School of Electrical and Electronic Engineering at NCEPU, where he is currently a professor. His areas of interest include power systems economics, power quality analysis and control, and new transmission and distribution technologies.

Yang Liu was born in Anhui Province, China. He received the B.S. degree in Thermal Energy and Power Engineering from North China Electricity Power University (NCEPU) in 2010. Currently, he is perusing a master degree in NCEPU and his research interest is power system analysis and control.

Meng Xiang was born in Hunan Province, China. She received the B.S. degree in Electrical Engineering from North China Electricity Power University (NCEPU) in 2010. Currently, she is perusing a master degree in NCEPU and her research interest is power system analysis and control.