

A New Probability Evaluation Model and Method of Wind Power Absorption Capability Based on Multi-Scenario Operation Simulation

Xuxia Li¹, Yao Wang², Yingying Hu³, Peng Wang⁴

¹Planning and Review Center, Economic and Electrical Research Institute of Shanxi Electrical Power Company of SGCC, TaiYuan, ShanXi, 030002, China

²Planning and Review Center, Economic and Electrical Research Institute of Shanxi Electrical Power Company of SGCC, TaiYuan, ShanXi, 030002, China

³Planning and Review Center, Economic and Electrical Research Institute of Shanxi Electrical Power Company of SGCC, TaiYuan, ShanXi, 030002, China

⁴Planning and Review Center, Economic and Electrical Research Institute of Shanxi Electrical Power Company of SGCC, TaiYuan, ShanXi, 030002, China

*Corresponding author's e-mail: 779656332@qq.com

Abstract. This paper proposed a probabilistic evaluation method of wind power absorption capacity considering interregional interaction based on multi-scenario operation simulation. The time scale of this method is pre-day, and many factors related to wind power absorption can be considered comprehensively, such as peak shaving capacity, frequency modulation capacity, load tracking capacity, rotating reserve capacity and network transmission capacity, which can provide a Multidimensional ratio evaluation of wind power absorption capacity which could identify the short-board factors that restrict wind power absorption. This paper provides a general framework for wind power absorptive capacity assessment. In the practical application of power system, the constraints can be flexibly chosen according to their own characteristics. The analysis results of the above examples show that the proposed method can effectively consider the inter-regional interaction, and can simulate and evaluate the system more accurately.

1. Overview

Wind power consumption means that the power system calls various resources to cooperate with the operation of wind power, so as to achieve the purpose of effective utilization of wind power. The scale of power system, the type of conventional unit, load characteristics and wind farm output characteristics will have an impact on the process of wind power absorption. The randomness and fluctuation of wind power output also determine whether the system can absorb wind power.

Generally speaking, the goal of wind power absorption in power system is to integrate and coordinate all kinds of resources in the system to improve system flexibility, which can not only make wind power be efficiently absorbed, but also make the system run safely, reliably and economically. Flexibility-related resources in the system include peak shaving capability, frequency modulation capability, load tracking capability, spinning reserve capability and network transmission capability. Only when a power system has sufficient system flexibility can there be no wind abandonment in the



process of wind power absorption. In China, the lack of flexibility in the power system aggravates the problem of abandonment. The evaluation of wind power absorptive capacity can quantify the capacity of the system to absorb wind power, and build a bridge between flexibility and absorptive capacity, so that the power system can quantify the future utilization of wind power in advance and play a proactive role.

At present, many studies have been carried out worldwide on the evaluation of grid-accommodable Wind Power Capacity (GWPC). There are many studies on GWPC evaluation in China, literature [1-3] studies wind power absorption capacity under peak shaving capacity; literature [4] studies wind power absorption capacity under peak shaving and network constraints; literature [5] studies peak shaving and frequency shaving capacity constraints and wind power absorption capacity; literature [6] considers peak shaving constraints and reserve constraints, and studies upper and lower limits of wind power output that can be absorbed. Some studies have also been carried out abroad about GWPC evaluation. Literature [7] studies GWPC evaluation considering transmission capacity of transmission lines in two-node power system; Literature [8] and [9] expand the evaluation method to actual power system on the basis of this study; Literature [10] and [11] take the reserve constraints into account, and use reliability-based reserve size determination method to evaluate GWPC. Literature [12-15] adopts probability evaluation methods, such as chance-constrained unit commitment, and references [16] and [17] consider load tracking constraints and frequency modulation capability constraints respectively in GWPC evaluation process.

However, the current research is limited to the evaluation of wind power absorptive capacity under the constraints of one or two factors. In fact, the size of wind power absorptive capacity depends on the short board factor of the power system, and that is the buckets effect. The power system truly needs a method to evaluate the wind power absorptive capacity, which can consider many key factors synthetically. Only in this way we could find the short-board factor accurately and the wind power absorptive capacity under the corresponding constraints can be obtained based on this factor.

this paper proposed a probabilistic evaluation method of wind power absorption capacity considering interregional interaction based on multi-scenario operation simulation. The time scale of this method is pre-day, and many factors related to wind power absorption can be considered comprehensively, such as peak shaving capacity, frequency modulation capacity, load tracking capacity, rotating reserve capacity and network transmission capacity, which can provide a Multidimensional ratio evaluation of wind power absorption capacity which could identify the short-board factors that restrict wind power absorption. This paper provides a general framework for wind power absorptive capacity assessment. In the practical application of power system, the constraints can be flexibly chosen according to their own characteristics [1].

2. The method of wind power absorption capacity assessment

The probabilistic evaluation model of wind power absorptive capacity based on multi-scenario operation simulation and considering interregional interaction is presented as follows. Firstly, the wind power output simulation is carried out based on the analysis results of wind power output characteristics, and the wind power output scenario library is generated. Then, the wind power output scenario library and the system load scenario Library are combined to generate the system operation scenario (L_i, W_j) , Furthermore, based on the results of interregional interaction behaviour modelling, the system running scenario will be simulated (Unit Commitment and Economic Dispatch, UCED). Finally, all system running scenarios (L_i, W_j) will be counted. The final probabilistic wind power absorptive capacity evaluation results can be obtained from the wind power absorptive situation.

2.1 Probabilistic Scene Generation

Probabilistic scenarios, which is wind power generation scenarios and system load scenarios, can be generated by two methods: historical statistics and sampling. Because historical data needs a lot of accumulation and is difficult to obtain, this paper uses sampling method to obtain wind power generation scenarios and system load scenarios. For the system load scenario, due to the accuracy of

day-ahead load forecasting is very high, this paper ignores the day-ahead load forecasting error, that is, there is only one system load scenario, that is, day-ahead load forecasting curve.

For wind power generation scenarios, the method of wind power output prediction is used to predict wind power output point in the next day. However, due to the high uncertainty of wind power output, the wind power output curve is generated from the point prediction results and the probability distribution of wind power prediction error, so that the wind power output scenario database is obtained. Each wind power output scenario has its own occurrence probability.

When given Φ 、 Ψ and a_{max} , $\theta^{a_{max}}$ could be calculated, by the total probability formula. As shown in the formula, it can be obtained by the expansion of the probability joint probability formula, in which the correlation between load and wind power output is neglected. When the wind power output is related to the load, it can also be considered in the process of generating the system operation scenario.

$$\begin{aligned}\theta^{a_{max}} &= E(u^{a_{max}}(a(L_i, W_j))) \\ &= \sum_{L_i \in \Phi} [p(L_i) \cdot E(u^{a_{max}}(a(L_i, \Psi)) | L_i)] \\ &= \sum_{L_i \in \Phi} [p(L_i) \cdot \sum_{W_j \in \Psi} [p(W_j | L_i) \cdot u^{a_{max}}(a(L_i, W_j))]] \\ &= \sum_{L_i \in \Phi} [p(L_i) \cdot \sum_{W_j \in \Psi} [p(W_j) \cdot u^{a_{max}}(a(L_i, W_j))]]\end{aligned}\quad (1)$$

This paper will generate N_{max} wind power generation scenario, whose size is determined by the accuracy convergence criterion of Monte Carlo methods. When given confidence level is $1 - \beta$ and tolerance of errors is ε , the samples of Monte Carlo should have no less than N :

$$N = \left(\frac{\lambda_\beta \hat{\sigma}}{\varepsilon / \theta^{a_{max}}} \right)^2 \quad (2)$$

Among them, λ_β is the quantiles corresponding to $1 - \beta$ of bilateral tests under standard normal distribution, $\hat{\sigma}$ is the estimation of standard deviation of error.

$$\hat{\sigma} = \sqrt{\frac{1}{N} \sum_{k=1}^N (u_k^{a_{max}})^2 - \left(\frac{1}{N} \sum_{k=1}^N u_k^{a_{max}} \right)^2} \quad (3)$$

2.2 System Operation Simulation

In order to evaluate the wind power absorption in each system operation scenario accurately, the system operation simulation technology is used to reproduce the power system operation. The time scale of operation simulation is hourly, and the objective function of operation simulation is the minimum wind abandonment. In the objective function, the economy is not considered, because this paper wants to explore the maximum acceptable wind power capacity of power system. The constraints of operation simulation can be divided into the following categories: basic constraints (BCs), Peak-valley Regulation Constraints (PRCs), Frequency Regulation Constraints (FRCs), Spinning Reserve Constraints (SRCs), Load-Following Constraints (LFCs), and Grid Transmission Constraints (GTCs).

2.2.1 Objective function

The objective of optimization is to minimize the amount of wind power discarded from the system.

$$\min \sum_{t \in \Omega_T} \sum_{w \in \Omega_W} C_w^t \quad (4)$$

Ω_T is the sets of unit assembly period, Ω_W is the sets for wind farms, C_w^t is the unit abandoned wind power in period of time T of unit W.

2.2.2 Constraint condition

➤ *Basic Constraints-Load Balance Constraints*

$$\sum_{i \in \Omega_G} P_i^t + \sum_{w \in \Omega_W} (W_w^t - C_w^t) + \sum_{l \in \Omega_L \cup \Omega_{TL}} L_{l,t} = \sum_{n \in \Omega_N} D_n^t, \forall t \in \Omega_T \quad (5)$$

In the formula (), Ω_G 、 Ω_N is the conventional unit set node set respectively, P_i^t is the active power for the unit i in the period time t , unit MW, W_w^t is the wind power prediction for wind farm w in the period of time t , unit MW, D_n^t is the node load for node n in the period of time t , unit MW.

➤ *Basic Constraints-Upper and Lower Power Limit Constraints of Units*

$$P_i^{\min} \leq P_i^t \leq P_i^{\max}, \forall t \in \Omega_T, i \in \Omega_G \quad (6)$$

In the formula (), P_i^{\min} and P_i^{\max} are the upper and lower limit output, unit MW.

➤ *Basic Constraints-Abandonment Constraints*

Abandoned wind power should not exceed the predicted wind power output.

$$0 \leq C_w^t \leq W_w^t, \forall t \in \Omega_T, w \in \Omega_W \quad (7)$$

➤ *Peak-shaving Constraints-Unit Start-Stop Number Constraints in Days*

$$u_{i,up}^t \geq I_i^t - I_i^{t-1}, \forall t \in \Omega_T, i \in \Omega_G \quad (8)$$

$$u_{i,down}^t \geq I_i^{t-1} - I_i^t, \forall t \in \Omega_T, i \in \Omega_G \quad (9)$$

$$\sum_{t \in \Omega_T} u_{i,up}^t \leq \bar{u}_{t,up}, \sum_{t \in \Omega_T} u_{i,down}^t \leq \bar{u}_{t,down}, \forall i \in \Omega_G \quad (10)$$

I_i^t is the unit state for the conventional units i in the period of time t , 1 represent power on, 0 represent power off; $u_{i,up}^t$ 、 $u_{i,down}^t$ indicating variables for the actual start-up and shutdown of the unit i during the period time t , $u_{i,up}^t = 1$ indicates that the time period t of the unit i has changed from stop state to start state, otherwise $u_{i,up}^t = 0$, $u_{i,down}^t = 1$ represents the time period t of the unit i from start-up to shutdown, $\bar{u}_{t,up}$ 、 $\bar{u}_{t,down}$ indicates The maximum number of start-ups and shutdown times in a day respectively.

Peak-shaving Constraints-Minimum Start-Down Time Constraints for Units

$$(I_i^t - I_i^{t-1})t_i^{\text{on}} + \sum_{j=t-t_i^{\text{on}}-1}^{t-1} I_i^j \geq 0, \forall t \in \Omega_T, i \in \Omega_G \quad (11)$$

$$(I_i^{t-1} - I_i^t)t_i^{\text{off}} + \sum_{j=t-t_i^{\text{off}}-1}^{t-1} (1 - I_i^j) \geq 0, \forall t \in \Omega_T, i \in \Omega_G \quad (12)$$

t_i^{on} 、 t_i^{off} indicate the Minimum start-up and shutdown time per hour for conventional units.

Network constraints

$$\left\{ \begin{array}{l} L_{l,t} = \sum_{k \in \Omega_N} g_{lk} \sum_{j \in \Omega_G} a_{kj}^G P_j^t - \sum_{k \in \Omega_N} g_{lk} D_k^t + \sum_{k \in \Omega_N} g_{lk} \sum_{w \in \Omega_W} a_{kw}^W (W_w^t - C_w^t) \quad l \in \Omega_L \\ -f_l^{\min} \leq L_{l,t} \leq f_l^{\max} \quad t \in \Omega_L \end{array} \right. \quad (13)$$

Among them, $L_{l,t}$ is the power of the transmission line l at time t , f_l^{\max} 、 f_l^{\min} are the maximum forward and reverse transmission power of transmission line, unit MW; Ω_L is the collection of lines; g_{lk} is the ranking element in the load transfer distribution factor G of generators. a_{kj}^G is the row k and column l element in the node correlation matrix A^G of conventional units. a_{kw}^W is the row k and column w element in the node correlation matrix of wind turbine A^W .

➤ *Load tracking constraints*

$$P_i^t - P_i^{t-1} + u_{i,up}^{t-1} (P_i^{\min} - \eta_{i,up} \Delta T) + u_{i,up}^t (P_i^{\max} - P_i^{\min}) \leq P_i^{\max}, \forall t \in \Omega_T, i \in \Omega_G$$

$$P_i^{t-1} - P_i^t + u_{i,down}^t (P_i^{\min} - \eta_{i,down} \Delta T) + u_{i,down}^{t-1} (P_i^{\max} - P_i^{\min}) \leq P_i^{\max}, \forall t \in \Omega_T, i \in \Omega_G \quad (14)$$

ΔT is the duration of each period in hours, $\eta_{i,up}$ 、 $\eta_{i,down}$ are the maximum rate of power rise and reduction per hour, unit MW/h.

➤ *Positive and Negative Standby Constraints*

$$\begin{aligned}
\sum_{i \in \Omega_G} I_i^t P_i^{max} + \sum_{w \in \Omega_W} W_w^t &\geq \sum_{n \in \Omega_N} (1 + r_{up}^t) D_n^t + \sum_{w \in \Omega_W} \gamma_{w,up}^t W_w^t, \forall t \in \Omega_T \\
\sum_{i \in \Omega_G} I_i^t P_i^{min} &\leq \sum_{n \in \Omega_N} (1 - r_{down}^t) D_n^t - \sum_{w \in \Omega_W} \gamma_{w,down}^t W_w^t, \forall t \in \Omega_T
\end{aligned}
\tag{15}$$

Among them, r_{up}^t, r_{down}^t are The positive and negative reserve rates of the system in the period time t respectively. $\sum_{w \in \Omega_W} \gamma_{w,up}^t W_w^t, \sum_{w \in \Omega_W} \gamma_{w,down}^t W_w^t$ are the positive and negative reserve provided by the system to deal with the prediction error of wind power output. $\gamma_{w,up}^t, \gamma_{w,down}^t$ are the ratio of positive conditional reserve and negative conditional reserve prepared by the system to deal with the prediction error of wind power which is related to the prediction level of wind power output. The research in reference [19] shows that the probability density function (PDF) of wind power output prediction error depends on its point prediction results. When the point prediction results are close to the upper and lower bounds, the prediction error has the characteristics of high deviation and low variance, and vice versa. Therefore, when the wind power forecast output is high, the system needs to provide more positive reserve, and when the wind power forecast output is low, the system needs to provide more negative reserve.

➤ *FM constraints*

$$-\frac{1}{\lambda_w} \sum_{w \in \Omega_W} [(W_w^t - C_w^t) - (W_w^{t-1} - C_w^{t-1})] + \frac{1}{\lambda_d} \sum_{n \in \Omega_N} (D_n^t - D_n^{t-1}) \leq \sum_{i \in \Omega_G} \eta_{i,up}^m, \forall t \in \Omega_T \tag{16}$$

$$\frac{1}{\lambda_w} \sum_{w \in \Omega_W} [(W_w^t - C_w^t) - (W_w^{t-1} - C_w^{t-1})] - \frac{1}{\lambda_d} \sum_{n \in \Omega_N} (D_n^t - D_n^{t-1}) \leq \sum_{i \in \Omega_G} \eta_{i,down}^m, \forall t \in \Omega_T \tag{17}$$

λ_d, λ_w are the hourly-minute variation coefficient of load and the hourly-minute variation coefficient of wind power.

The results of analysis in reference [20] show that the variation range of load fluctuation in hourly stage is much larger than that in minute stage, and there is a relationship between 15 and 40 times. λ_d represents the ratio of hourly and minute changes. The research in reference [21] shows that the fluctuation range of the minute output of the wind farm in Jeju Island is about 13% of the installed capacity of the wind farm, while the fluctuation range of the general hourly output can vary between 0% and 100% of the installed capacity of the wind farm. Therefore, the ratio of the fluctuation range of the hourly output to the fluctuation range of the minute output is 13%. In this paper, the fluctuation range of the hourly output of the wind farm is 13% which is λ_w . for large-scale wind power, due to its wind power output, there exists smoothing effect. Generally less than 13%, so the range of variation λ_w is [8,15]. When the fluctuation of the equivalent load (the difference between the original load and the output of wind power) in the minute level exceeds the regulation ability of the minute level of the system, the system will abandon the wind.

2.3 Model description

Based on the introduction of the above models, the overall model is sorted out as shown in the formula (25). The optimal variables of the model are $\{I_i^t, u_{i,up}^t, u_{i,down}^t, P_i^t, C_w^t\}, \forall t \in \Omega_T$. It should be pointed out that in order to be general, the operation simulation model established in this section takes into account the common constraints of wind power absorption in power system. But due to different power systems have different characteristics, the objective functions and constraints of the corresponding unit commitment and dispatch models are also different. In the practical application of the operation simulation model, the power system can flexibly consider different objective functions and constraints according to its own characteristics, that is, the model adopted in this section has strong generality.

$$\begin{aligned}
& \min \sum_{t \in \Omega_T} \sum_{w \in \Omega_W} C_w^t \\
& \text{s.t.} \\
& \left\{ \begin{aligned}
& \sum_{i \in \Omega_G} P_i^t + \sum_{w \in \Omega_W} (W_w^t - C_w^t) + \sum_{l \in \Omega_L \cup \Omega_{TL}} L_{l,t} = \sum_{n \in \Omega_N} D_n^t \\
& P_i^{\min} \leq P_i^t \leq P_i^{\max}, \forall i \in \Omega_G \\
& 0 \leq C_w^t \leq W_w^t, \forall w \in \Omega_W \\
& u_{i,\text{up}}^t \geq I_i^t - I_i^{t-1}, \forall i \in \Omega_G \\
& u_{i,\text{down}}^t \geq I_i^{t-1} - I_i^t, \forall i \in \Omega_G \\
& \sum_{t \in \Omega_T} u_{i,\text{up}}^t \leq \bar{u}_{i,\text{up}}, \sum_{t \in \Omega_T} u_{i,\text{down}}^t \leq \bar{u}_{i,\text{down}}, \forall i \in \Omega_G \\
& (I_i^t - I_i^{t-1}) t_i^{\text{on}} + \sum_{j=t-t_i^{\text{on}}-1}^{t-1} I_i^j \geq 0, \forall i \in \Omega_G \\
& (I_i^{t-1} - I_i^t) t_i^{\text{off}} + \sum_{j=t-t_i^{\text{off}}-1}^{t-1} (1 - I_i^j) \geq 0, \forall i \in \Omega_G \\
& L_{l,t} = \sum_{k \in \Omega_N} g_{lk} \sum_{j \in \Omega_G} a_{kj}^G P_j^t - \sum_{k \in \Omega_N} g_{lk} D_k^t + \sum_{k \in \Omega_N} g_{lk} \sum_{w \in \Omega_W} a_{kw}^W (W_w^t - C_w^t), \forall l \in \Omega_L \\
& -f_i^{\min} \leq L_{l,t} \leq f_i^{\max}, \forall l \in \Omega_L \\
& -RD_l^{A \leftarrow B} \leq L_{l,t+1} - L_{l,t} \leq RU_l^{A \leftarrow B}, \forall l \in \Omega_{TL} \\
& P_i^t - P_i^{t-1} + u_{i,\text{up}}^{t-1} (P_i^{\min} - \eta_{i,\text{up}} \Delta T) + u_{i,\text{up}}^t (P_i^{\max} - P_i^{\min}) \leq P_i^{\max}, \forall i \in \Omega_G \\
& P_i^{t-1} - P_i^t + u_{i,\text{down}}^{t-1} (P_i^{\min} - \eta_{i,\text{down}} \Delta T) + u_{i,\text{down}}^t (P_i^{\max} - P_i^{\min}) \leq P_i^{\max}, \forall i \in \Omega_G \\
& \sum_{i \in \Omega_G} I_i^t P_i^{\max} + \sum_{w \in \Omega_W} W_w^t \geq \sum_{n \in \Omega_N} (1 + r_{\text{up}}^t) D_n^t + \sum_{w \in \Omega_W} \gamma_{w,\text{up}}^t W_w^t \\
& \sum_{i \in \Omega_G} I_i^t P_i^{\min} \leq \sum_{n \in \Omega_N} (1 - r_{\text{down}}^t) D_n^t - \sum_{w \in \Omega_W} \gamma_{w,\text{down}}^t W_w^t \\
& -\frac{1}{\lambda_w} \sum_{w \in \Omega_W} [(W_w^t - C_w^t) - (W_w^{t-1} - C_w^{t-1})] + \frac{1}{\lambda_d} \sum_{n \in \Omega_N} (D_n^t - D_n^{t-1}) \leq \sum_{i \in \Omega_G} \eta_{i,\text{up}}^m \\
& \frac{1}{\lambda_w} \sum_{w \in \Omega_W} [(W_w^t - C_w^t) - (W_w^{t-1} - C_w^{t-1})] - \frac{1}{\lambda_d} \sum_{n \in \Omega_N} (D_n^t - D_n^{t-1}) \leq \sum_{i \in \Omega_G} \eta_{i,\text{down}}^m
\end{aligned} \right. \\
& \forall t \in \Omega_T
\end{aligned} \tag{18}$$

3. Wind Power Absorption Capacity Assessment Model

The flow chart of the GWPC evaluation model is shown in Figure 1. Based on the load scenario L_i to generate a wind power generation scenario N_{max} , at the same time, it could generate corresponding system running scenarios (L_i, W_j) , The system operation simulation is used to get the wind power absorption of each system operation scenario. Finally, the calculation results $\theta^{a_{max}}$ are obtained.

By using this evaluation model, the wind power absorption capacity can be analysed from multiple perspectives.

1) By adjusting the output level of wind power, the wind power absorption capacity $A_W^{a_{max}}$ of the system can be explored.

2) By adjusting the constraints of the operation simulation system, we can explore the influence of each group of constraints on the wind power absorption of the system, and find out the key factors that restrict the wind power absorption. The specific operation method is to evaluate the wind power absorption capacity considering all constraints and single constraints respectively. The most proportion factor restricting wind power absorption is the key factor of wind power absorption.

3) Can be adjusted To explore the wind power absorption under different wind abandonment tolerance.

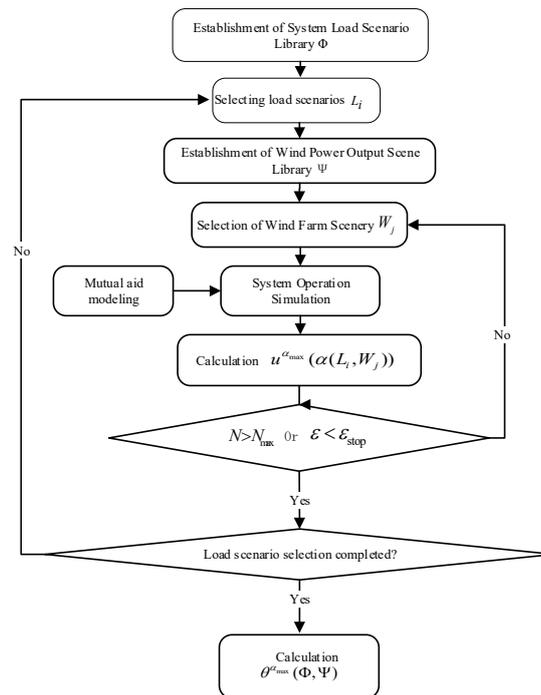


Figure 1. Calculation flow chart of GWPC evaluation model

4. Example Analysis

In this paper, we use a IEEE 39-Node Standard Test System, as shown in Figure 2. In this example, all parameters of the system are taken from Matpower 4.0[22], and the other parameters are set as shown in Table 1. In the system, the total capacity of 10 conventional units is 2807 MW. On this basis, the units on #8 node and #13 node are replaced by two wind farms. The installed capacity of wind power is 804 MW and 933 MW, respectively. The total installed capacity of wind power is 1737 MW, accounting for 19.1% of the total installed capacity of the system.

At the same time, it is assumed that at node 21, a tie line is shared with the external power system, and its parameters are the same as those between node 16 and node 21. The external system and the system agreed to provide 100 MW power to the external system at the low load time, i.e. from 2:00 to 6:00, and to receive 200 MW power from the external system at the peak load time, i.e. from 18:00 to 22:00, while the power of the tie-line at other times is zero.

The UCED model of system operation simulation is solved by CPLEX.[23]

4.1 System Load Scene and Wind Power Output Scene

The wind power generation scenarios based on the probability distribution of wind power prediction error in reference [19] are generated. As shown in figure 3 is typical wind power generation scenarios of 8 # wind farm.

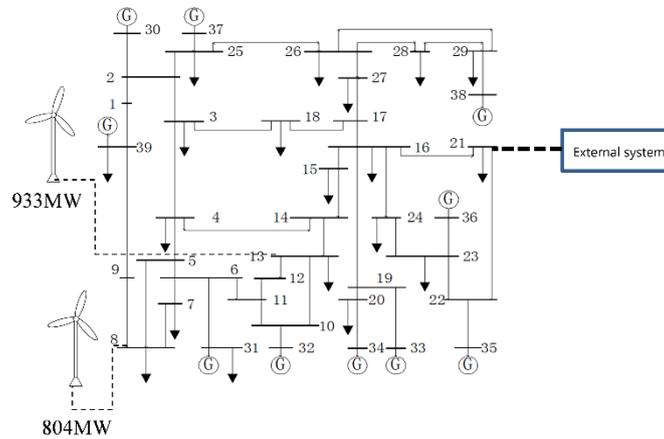


Figure 2. IEEE 39-Node Standard Test System

Table 1. Examples for parameter setting of test system

Parameter type	Parameter value
p_i^{\max}, p_i^{\min}	Installed capacity of 100%, 50%
$r_{\text{up}}^t, r_{\text{down}}^t$ (%/hour)	5, 5
$\eta_{i,\text{up}}^h, \eta_{i,\text{down}}^h$ (%/hour)	100, 100
$\eta_{i,\text{up}}^m, \eta_{i,\text{down}}^m$ (%/min)	1.67, 1.67
λ_d, λ_w	15, 10
$t_i^{\text{on}}, t_i^{\text{off}}$	20, 1
$\bar{u}_{i,\text{up}}, \bar{u}_{i,\text{down}}$	1, 1
β (%)	99.7
ϵ_{stop}	0.05
N_{max}	200

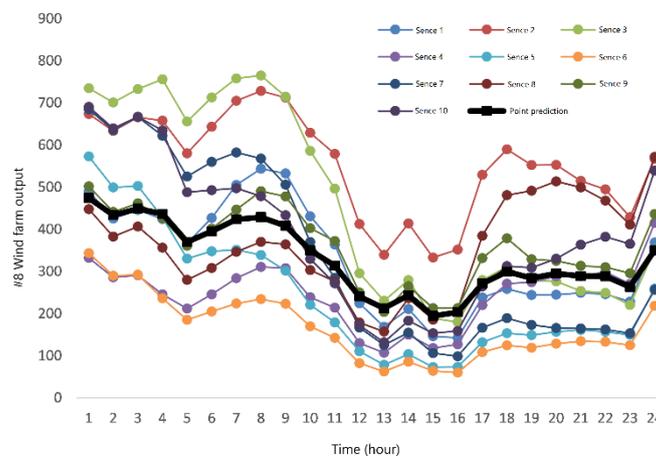


Figure 3 #8 Wind Farm Output Curve

At the same time, the conditions to prepare for wind power prediction errors are reserved which is $(\gamma_{i,\text{up}}^t, \gamma_{i,\text{down}}^t)$ shown in figure 4.

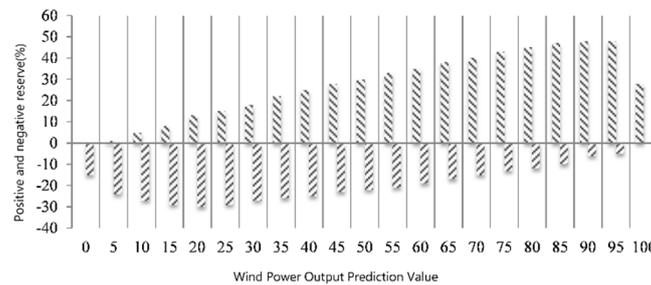


Figure 4. Positive and Negative Reserve Ratio of Wind Power under Different Wind Power Output Prediction Levels

5. Summary of Case Analysis

The analysis results of the above examples show that the proposed method can effectively consider the inter-regional interaction, and can simulate and evaluate the system more accurately. At the same time, the evaluation process takes into account the constraints of many factors, and can effectively identify the key factors that restrict the wind power absorption at different wind power output levels, and can also be based on the abandoned wind capacity of the system. The tolerance can get the corresponding wind power absorption capacity.

Acknowledgement

Science and technology support project of State Grid Corporation of China, Contract number: SGSXJY00PSJS1800016

References

- [1] G. Chonghui, W. Xi, F. GuoYing, (2014) Analysis on Jilin Wind Power Consumption Ability After Large Scale Integration. *JuLin Power*. vol.42(5), pp.1-4,7.
- [2] L. Yong, T. XiaoJun, X. BaoAn, (2012) Grid Capacity of Wind-power Algorithm Analysis. *Hebei Electric Power*. vol.31(2), pp.21-22.
- [3] L. Chang, W. Hao, G. ChangZheng, (2014) Study on analysis method of accommodated capacity for wind power, *Power System Protection and Control*, vol.42(4), pp.61-66.
- [4] L. WeiDe, H. YueHui, W. WeiSheng. (2013) Analysis on Provincial System Available Capability of Accommodating Wind Power Considering Peak Load Dispatch and Transmission Constraints, *Automation of Electric Power Systems*, vol.37(7), pp.1887-1894.
- [5] J. WenZhao, Y. Bing, Y. ZhiGang, (2014) Assessment of Wind Power Accommodation and Ability of Peak Regulation and Frequency Modulation, *North China Electric Power*, vol.5, pp.10-16.
- [6] J. WenZhao, K. ChongQing, L. Dan, (2012) Evaluation on Capability of Wind Power Accommodation Based on Its Day-ahead Forecasting, *Power System Technology*, vol.36(8), pp.69-75.
- [7] J. Sveca, L. Soder. (2003) Wind power integration in power systems with bottleneck problems. *Power Tech Conference Proceedings*, vol.2, pp.23-26.
- [8] J. Burke D, M. O'Malley. (2009) Transmission connected wind curtailment with increasing wind capacity connection. *Proceedings of IEEE Power and Energy Society General Meeting*, vol,1, pp.1-5
- [9] J. Burke D, M. O'Malley. (2009) Optimal firm wind capacity allocation to power systems with security constraints. *Power Systems Conference and Exposition*, vol.1, pp.1-9.
- [10] R. Doherty, M. O'Malley. (2005) A new approach to quantify reserve demand in systems with significant installed wind capacity. *IEEE Transactions on Power Systems*, vol.20(2), pp.587-595

- [11] Ding Y, Wang P, Goel L, et al. (2011) Long-term reserve expansion of power systems with high wind power penetration using universal generating function methods. *IEEE Transactions on Power Systems*, vol.26(2),pp.766-774.
- [12] Akhavan-Hejazi H, Mohsenian-Rad H. (2014) Optimal operation of independent storage systems in energy and reserve markets with high wind penetration. *IEEE Transactions on Smart Grid*, 5(2):1088-1097.
- [13] Silva A M L, Sales W S, Fonseca L A M, et al. (2010) Long-term probabilistic evaluation of operating reserve requirements with renewable sources. *IEEE Transactions on Power Systems*, vol. 25(1):106-116.
- [14] Morales J M, Conejo A J, Pérez Ruiz J. (2009) Economic valuation of reserves in power systems with high penetration of wind power. *IEEE Transactions on Power Systems*, 24(2):900-910.
- [15] Murillo-Sanchez C E, Zimmerman R D, Anderson C L, et al. (2014) Secure planning and operations of systems with stochastic sources, energy storage, and active demand. *IEEE Transactions on Smart Grid*, 4(4):2220-2229.
- [16] Makarov Y V, Loutan C, Ma J, et al. (2008) Impacts of wind generation on regulation and load following requirements in the California system. *Proceedings of IEEE Power and Energy Society General Meeting*, 1:1-9.
- [17] Chavez H, Baldick R, Sharma S. (2012) Regulation adequacy analysis under high wind penetration scenarios in ERCOT nodal. *IEEE Transactions on Sustainable Energy*, 3(4):743-750.
- [18] Zhang N, Kang C, Duan C. (2010) Simulation methodology of multiple wind farms operation considering wind speed correlation. *International Journal of Power and Energy Systems*, 30(4):264-273.
- [19] Zhang N, Kang C, Xia Q, et al. (2014) Modeling conditional forecast error for wind power in generation scheduling. *IEEE Transactions on Power Systems* 29(3):1316-1324.
- [20] Hirst E, Kirby B. Defining intra and inter hour load swings. *IEEE Transactions on Power Systems*, 1998, 13(4):1379-1385.
- [21] Kim Y H, Kim S H. (2009) Variations of wind power generation in Korea-Jeju power system. *Transmission & Distribution Conference & Exposition: Asia and Pacific*, 1:1-4
- [22] Zimmerman R D. (2010) MATPOWER 4.0b4 User's Manual.
- [23] The IBM ILOG CPLEX website, (2011). [EB/OL]. Available: <http://www-01.ibm.com/software/websphere/products/optimization/academic-initiative/index.html/>.
- [24] Probability Methods Subcommittee. (1979) IEEE Reliability Test System. *IEEE Transactions on Power Apparatus and Systems*, PAS-98(6):2047-2054.