A method suitable for comprehensive assessment of wind power penetration capability of regional power grids including multiple wind farms

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Abstract—This paper proposes a comprehensive assessment method of wind power penetration capability for multiple points of connection of wind farms, considering peak load regulation, static security, static voltage stability and transient stability constraints of power system. A mathematical model of the comprehensive assessment method is built, and the calculation process of the wind power penetration capability for multiple points of connection is designed. An actual regional power grid in a province is taken as an example to proven the validity of the proposed method.

Keywords: wind power penetration capability; comprehensive assessment method; multiple wind farms; peak load regulation; static security.

I. INTRODUCTION

Research on wind power penetration capability attaches great significance: on the one hand, the wind power resources can be fully developed; on the other hand, excessive scale of the wind power capacity can be avoided.

The wind farm penetration capability is mainly constrained by the system peak load regulation [1, 2], the static security [3, 4], the static voltage stability [5] and the system transient stability [6,7]. The characteristics of the main constraints are as follows. The peak load regulation constraint is only related with the structure of power sources, load characteristics and the inter-regional tie–line power adjustment ability, regardless of the specific points of connection. While the other three constraints is related to the specific points of connection, of which the static security and system transient stability constraint are mainly used as means of verification for determined wind farm capacity at each points of connection. Generally, the points of connection of wind farms are chosen considering the positions of the wind power resources. When multiple points of connection of wind farms are within a regional grid, the maximum wind power penetration capability of the each points of connection influences each other [8].

This paper proposes a comprehensive assessment method of the wind power penetration capability of multiple grid-connected wind farms. Firstly, the mathematical model of a regional grid's wind power penetration capability is given. Secondly, the calculation process is designed to assess the wind power penetration capability of multiple grid-connected wind farms. Finally, a regional grid is used as an example to validate the effectiveness of this proposed method.

II. THE COMPREHENSIVE ASSESSMENT METHOD OF THE WIND POWER PENETRATION CAPABILITY

A. The mathematical model

The regional maximum wind power penetration capability is S_{wind},

$$S_{wind} = \sum_{i=1}^{N_w} S_{windi} \qquad (1)$$

In (1), S_{windi} is the capacity of wind farm i, N_w is the set of wind farms.

Constraints are as follows:

$$s.t. \begin{cases} P_{gi} + P_{windi} - P_{Li} - U_i \sum_{j=1}^{N_s} U_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0 \quad i \in N_S \\ Q_{gi} + Q_{windi} - Q_{Li} - U_i \sum_{j=1}^{N_s} U_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0 \quad i \in N_S \end{cases} \qquad (2)$$

$$\begin{cases} S_{windi} \le S_{resourcei}, i \in N_w \\ S_{wind} \le S_{peak} \\ 0 \le P_{li} \le P_{l\max}, i \in N_l \\ P_{gi\min} \le P_{gi} \le P_{gi\max}, i \in N_g \\ U_{i\min} \le U_i \le U_{i\max}, i \in N_s, 0 \le P_{wj} \le S_{windj}(j \in N_w) \\ I_{si} < I_{SN}, i \in N_s \end{cases} \qquad (3)$$

Equation(2) is the power flow equality constraint, in which, N_S is the set of all nodes, P_{gi} and Q_{gi} are the injected real and reactive power into node i, P_{windi} and Q_{windi} are the injected real and reactive power into the wind farm i, P_{Li} and Q_{Li} are the real and reactive power of the load at node i, U_i and U_j are the voltages of node i and j respectively, G_{ij} and B_{ij} are the real and imaginary parts of the admittance of branch $i - j$, θ_{ij} is the phase angle difference of branch $i - j$.

Equation(3) are the inequality constraints, in which, $S_{resourcei}$ is the available capacity of the wind farm i, N_w, N_l, N_g, N_s are the sets of the wind farms, branches, nodes of the generators and the total nodes respectively, S_{peak} is the maximum wind power penetration capability considering peak load regulation constraint, $P_{gi\,max}$ and $P_{gi\,min}$ are the upper and lower real power limits of generator i, $U_{i\,max}$ and $U_{i\,min}$ are the upper and lower voltage limits of node i, I_{si} and I_{SN} are the short circuit current of node i and the related breaker capacity respectively.

The above considered inequality constraints are as follows:

1) *The capacity of a wind farm is smaller than its resource capacity (available wind power capacity at the point of connection).*

2) *The sum of all wind farm capacity is smaller than the maximum wind power penetration capability constrained by peak load regulation.*

3) *Static security constraints: the power constraints of the transmission lines, the power constraints of generators.*

4) *With the change of the wind farm output, the voltages of the monitoring nodes are not beyond the limits.*

5) *The level of the system short circuit is not exceeded with the integration of certain wind power capacity, and system transient stability should be kept in case of failures.*

B. The calculation process

The overall train of thought to assess the wind power penetration capability in a region is about three steps. Firstly, calculate the wind power penetration capability based on the peak load regulation constraint. Secondly, compute the wind power capacity of the different grid-connected points based on static security and static voltage stability constraints. Lastly, verify the wind power penetration capability by system transient stability constraint. The flow path of the calculation is shown as Fig .1.

The specific calculating process is as follows:

1) *Calculate the max wind power penetration capability S_{peak} based on peak load regulation constraint [9-10].*

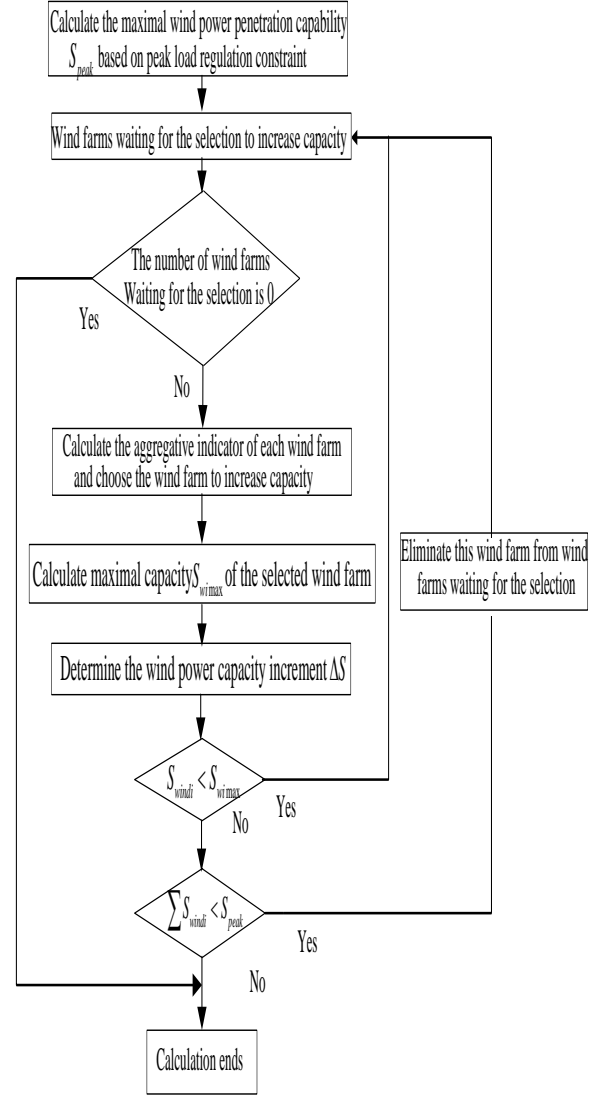
Figure 1. Flow path of calculating the wind power penetration capability of multiple wind farms.

2) *Select the wind farm to increase the capability.* The wind farm i is selected by the optimization aggregative indicator as (4).

$$\lambda_i = -\alpha_1 \Delta Q_i + \alpha_2 P_{lsi} + \alpha_3 P_{resourcei}, i \in N_w \qquad (4)$$

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \qquad (5)$$

In (4), ΔQ_i is the reactive power margin of the weakest node in voltage, which takes the per unit value using the system base value. A positive reactive power margin means that the system is insufficient in reactive power, so a negative sign is added before the indicator. P_{lsi} equals the difference between transmission limit and the load of the out-sending line of wind farm i of which the load rate is highest. It takes the per unit value with its transmission limit as the base value. $P_{resourcei}$ is the difference value between resource capacity and existing capacity of wind farm i, which also takes the

per unit value using the system base value. $\alpha_1, \alpha_2, \alpha_3$ is the weight coefficient of each indicator. In this paper, $\alpha_1 = 0.50, \alpha_2 = 0.25, \alpha_3 = 0.25$, priority is given to the reactive power margin. The wind farm with the largest aggregative indicator is selected.

3) *Considering peak load regulation,* static security, static voltage stability, and s wind resource constraints in (3), calculate maximal capacity $S_{wi\max}$ of the selected wind farm.

4) *Determine the wind power capacity increment* ΔS *for the selected wind farm.* The original value of ΔS is 20MW, and the capacity of the wind farm should be less than $S_{wi\max}$ subsequent to the increment, as shown in (6).

$$\Delta S = \begin{cases} 20, & S_i + 20 \le S_{wi\max} \\ S_{i\max} - S_i, & S_i + 20 > S_{wi\max} \end{cases} \qquad (6)$$

In (6), S_i is the capacity of wind farm before increment.

5) *Judge whether the selected wind farm capacity has reached the maximum, if not, repeat (b)-(d) steps.* Otherwise, judge the reason for the maximum. If the reason is peak load regulation constraint, the computing process ends; if not, remove the wind farm from those to be selected and repeat (b)-(d) steps. The computing process ends until the total of wind farm capacity reaches S_{peak} or the number of wind farms waiting for selection is 0.

6) *Verify whether the system stability is satisfied or not with the wind farm capacity.* If not, reduce the limit of the total wind farm capacity by decreasing the value of S_{peak}, and recalculate until the system transient stability is satisfied.

III. CASE STUDY

An actual regional grid is taken as an example. The maximal wind power penetration capability based on peak load regulation constraint is 1560MW in 2020. There are nine planned wind farms in this region, they concentrate on two areas. As shown in Fig .2, the voltage of thicker blue lines is 220 kV, the thinner green lines 110 kV.
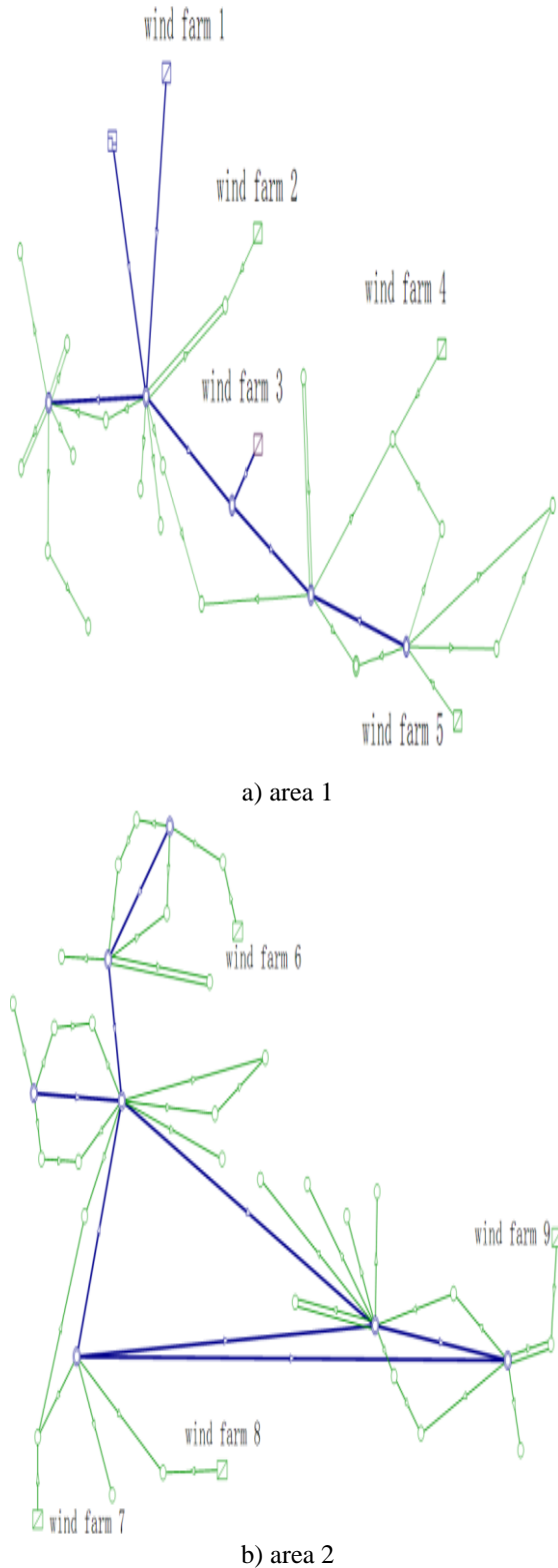

a) area 1

b) area 2

Figure 2. Wind farm grid-connection graph of the studied region.

With the regional power grid data model and resource capacity of each wind farm, the maximal wind power capacity of each points of connection is calculated by BPA. The calculation process is shown in TABLE I.

calculation process	the chosen wind farm	the wind farm capacity after increment / MW	the limited wind farm capacity condition
1	wind farm 3	20	none
2	wind farm 1	20	none
3	wind farm 5	20	none
. .	. .	. . .	. . .
12	wind farm 1	100	none
13	wind farm 5	87	resource capacity limit
. .	. .	. . .	. . .
24	wind farm 1	192	resource capacity limit
25	wind farm 3	192	resource capacity limit
. .	. .	. . .	. . .
37	wind farm 2	99	resource capacity limit
38	wind farm 4	144	resource capacity limit
. .	. .	. . .	. . .
50	wind farm 7	120	surpass lower voltage limit
. .	. .	. . .	. . .
54	wind farm 9	80	surpass lower voltage limit
55	wind farm 6	96	resource capacity limit
56	wind farm 8	80	resource capacity limit
57	wind farm 8	96	resource capacity limit

Verification shows that the system stability is satisfied with the calculated wind farm capacity. Therefore, the wind power penetration capability of each wind farm from 1-9 is 192, 99, 192, 144, 87, 96, 120, 96, 80 MW respectively.

IV. CONCLUSION

Based on the constraints of the wind power penetration capacity, this paper proposes a comprehensive assessment method for multiple wind farms. The mathematical model is built, and the realizing calculation process is designed. An aggregative indicator is used to select the wind farm to increase capacity so that the obtained wind power penetration capacity is optimal in the aspects of reactive voltage, static security and wind power capacity. The increment of wind power capacity is determined considering the peak load regulation, static security, and static voltage stability constraints to ensure the safe and stable operation of power system. The wind power penetration capacity is obtained through multiple iterations, and the system transient stability is verified to get the final acceptance of wind power capacity.

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