Research on the Qualitative and Quantitative Analysis of Wind Power Acceptable Capacity

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Abstract. With the rapid development of wind power, wind power grid-tied become the bottleneck of wind power development. In this paper, from two aspects, qualitative and quantitative analysis of the influencing factors of wind power acceptable capacity, the specific quantitative method is given to select access location and determine the maximum power injection of wind farms. Assessing the influence of voltage level and network loss when the wind farm is connected to the power grid, which are prioritized and then determine the reasonable grid connection point. By adopting the combination of static and dynamic analysis method to determine the maximum power injection. First, determine the maximum power injection of wind farms by the static constraint conditions, and then, get the wind power which can keep the grid transient stability by considering the influence of wind speed change and power grid fault mode in the transient analysis, which is the acceptable maximum wind power of that grid connection point. Finally, measures to raise the capacity of wind power acceptance are given on the basis of research above.

Introduction

In the development of wind power, there are many technical problems to be solved, which cannot be ignored is the analysis of wind power acceptable capacity of power grid. Acceptance capacity refers to the maximum acceptance of wind power capacity under the premise that safety, stability and economic operation of the power grid, which also known as the maximum wind power injection or limit of wind power injection. Research on Wind power acceptable capacity mainly from select access location and calculate the maximum power injection of wind farms. Quantitative results are obtained from a comprehensive analysis of the stability characteristics of wind power integration.

In the quantitative analysis of wind power acceptable capacity of power grid injection, most of the researches on wind power limit used digital simulation method to analysis the influence on the quality and stability of the system when wind power fluctuation, and then, determine wind power limit of system [1].Rough indicators, such as, determine the scale of wind farm according to the short circuit capacity of the wind farm access point. Part of the research only consider static security constraints, the literature[2]asynchronous generator steady-state mathematical model is established, through the power flow calculation, obtain the wind power that meet the static safety of wind power with the method of PV curve. The literature[3]solve the problem of wind power maximization under the static security constraints with optimization method, determine the wind power limit and give the optimal scheduling scheme of other regular unit in the system. At present, about dynamic stability research mainly focus on modeling and verifying the model of the wind farm, and there is no engineering application in the large power grid technology[4-7], the literature[4]analyzed the different wind turbines on the effect of dynamic characteristic of grid; Literature[5]dynamic stability calculation is required for wind farm when connected to the electricity grid, and also introduces the research direction in wind turbine simulation modeling; Literature[6]established the dynamic model of asynchronous wind
turbines and doubly-fed wind power generator, the analysis shows that the main limit factor of asynchronous wind turbines access grid is the node voltage exceeding caused by wind power injection, and the main factor influencing the doubly-fed wind power generator is the line transmission capacity; Literature (7) one calculation method is proposed based on the analysis of system dynamic stability of wind farm penetration power limit. Respectively by using dynamic digital simulation method, dynamic simulation experiments were performed for many times under different wind power access constraints such as the frequency (8-9) peaking capability and static security with the assumed wind power, and constantly revised p-value until meet the restriction condition, finally determine wind power penetration power limit.

Based on the qualitative and quantitative analysis of the influencing factors of wind power acceptable capacity, the specific quantitative method is given to select access location and determine the maximum power injection of wind farms, by adopting the combination of static and dynamic analysis constraints to determine the maximum power injection, measures to raise the capacity of wind power acceptance are given on the basis of research above.

Qualitative Analysis of Wind Power Acceptable Capacity

First, qualitative analysis of the factors influencing the power grid acceptance of wind power capacity, as shown in figure 1, which is mainly analyzed from the two aspects of the grid side and wind power itself.

The main influencing factors of grid side are in the following aspects:

(1) structure of the power source and its regulating ability
When the large-scale wind power is connected to the grid, because randomness and the anti-peak shaving characteristics of the wind power, other power sources are needed to help balance the load demand. However, the power sources are mainly thermal power in the rich wind power areas, thermal power units take a high proportion, and lack of the fast start power supply like the pumped storage units and gas turbine units. The regulation ability of thermal power unit is poor; these electric sources are disadvantage to large-scale wind power access. Therefore, the scale of wind power connected grid is restricted by the electric source structure and regulating ability of the grid.

(2) grid structure
Areas with rich wind energy resources are usually far from the load center, the wind power cannot be local consumed, it would be send through the transmission network to the load center by long distance. When the large-scale wind power transmission over a long distance, the line voltage drop and the line loss are increased, the acceptance ability of wind power is constrained. In addition, the transmission capacity of the line is also a major factor for the poor power transmission ability.

(3) load characteristic
Because wind power has the characteristics of anti-peak shaving, wind power capacity allowance of the grid is directly determined by the grid load type, load level and peak valley difference.

(4) power grid operation level

Figure 1. Influencing factors of Acceptable Capacity.
The power grid operation cannot take into account the output of wind power when the capacity of wind power integration is small, the traditional power supply (thermal power) adjustment capacity can be used in complete the power balance. When the wind power grid capacity increase gradually, it is necessary to improve the operation level of the grid to realize the acceptance of wind power, such as the smart grid technology, Optimal dispatching technology, etc.

(5) the energy storage capacity

Energy storage system applied to the wind farm grid system can effectively smooth wind power output, increase controllability of wind farm output, energy storage system is adding a "store" power section in the power grid, which makes the almost “rigid” original system “flexible” and provides adjustable, controllable, movable power to the load side.

The main influencing factors of wind turbines are in the following aspects:

(1) the type of wind turbines

The performance of doubly fed induction generator and direct driven wind turbine is obviously better than that of stall induction turbine.

(2) Low voltage ride through capability

At present, the test of the low voltage ride through of wind turbines is carried out by the State Grid, with this way can ensure that the turbines would not take off the grid when the power grid fails, and provides active power to support the system before the other power supply respond without collapsing the system.

(3) the wind farm reactive power compensation

Because the voltage security of wind farm is the main problem of wind power access system, the reactive power/voltage characteristic of the system is very important to the wind farm, reactive power compensation equipment, such as SVC, can improve the voltage stability of wind farms, which also increases the wind power capacity of the grid.

(4) Wind power forecasting technology

Accurate wind power forecasting technology, which helps the power dispatching department make reasonable daily operation mode in time, accurately adjust the scheduling plan, and then enhancing the wind power capacity into the grid

Quantitative Calculation of Wind Power Acceptable Capacity

The above is a qualitative analysis of the wind power acceptable capacity of the grid, so quantitative analysis would be needed. First of all, the location of the wind farm connected to the power grid should be determined. There is no standard method for the selection of wind farm location, the existing sensitivity analysis method and the continuation power flow method are used in finding the weak point of the grid voltage, and then best access position of the wind farm can be found. This paper is based on the existing literature, considering the wind farm integration will change the distribution of the regional power grid, and then change the network loss of the system and affect the economy of the system operation. Therefore, the reasonable location of wind farm can be getting from comprehensive analysis and quantification of voltage stability level of power grid and network loss.

About the selection of index of voltage stability, considering the power injection of wind change the trend of the distribution of the system, and it has the large impact on node voltage of system, the voltage at the node is very close to the upper and lower limits of its qualification range, which would reduce the rate of voltage compliance, and become a safe operation of the system risks. Therefore, in order to accurately quantify the stability level of the grid voltage, a new definition is put forward, namely the grid voltage exceeds the limit distance. Specifically to quantify the stability of the grid voltage, grid voltage exceeds the limit distance is defined as the distance between the current running point voltage of the grid and the voltage target value of the normal operation, specific calculation method reference formula 1. Aiming at large-scale wind farm integration, this "distance D" refers to the difference in the key parameter values between the overall voltage level of the grid after wind farm
Integration and the target level of the normal operating voltage, the smaller the better. As a result, this index can be used as a quantitative method to estimate the voltage stability margin of the current operating point.

\[
D = \frac{\sum_{i=1}^{N} |U_{i}^{\text{opt}} - U_{i}|}{U_{i}^{\text{opt}} N}
\]

Thus: \(U_{i}^{\text{opt}}\) refer to the voltage target value of the grid for normal operation; \(U_{i}\) refer to the voltage value at the node \(i\) of operation; \(N\) refer to the number of grid evaluation points.

Maximum Wind Power Injection Determination

Existing method to determine the maximum power injection of wind farms is mainly the time domain simulation method, the static security constraint method, short circuit capacity method and frequency constraint method. These studies often use relatively crude indicators to determine the capacity of wind farm access systems; even only consider the static security constraints of the grid without considering the dynamic security requirements of the system under large disturbances. This paper proposes a combination of static and dynamic constraints of synthesis method to calculate the maximum power injection of wind farms.

Calculation Method

(1) The method of static constraint

Static safety constraint method is through the power flow calculation, which can get the maximum capacity of the wind farm to satisfy the static safety constraints of the power system. It is necessary to check whether the voltage of wind farm grid-connected points, the voltage of each node in the system and the active power transmitted over the line are exceeded. However, wind farms are usually in the end of the power grid, the grid space truss structure is weak, after the wind farm connected to the grid, with the output of wind power changing, the distribution of power flow, voltage level and power angle difference \(\delta\) are also changing, the result is optimistic if the static security constraints is only considered; therefore, the dynamic security constraint of the system must be considered.

(2) The method of dynamic constraint

The dynamic safety constraint method is under certain steady state, if there is a big disturbance in the system or a sudden fluctuation of wind speed in the wind farm, the maximum capacity of the wind farm with stable operation. Dynamic simulation is actually to investigate the transient stability of the system; it is necessary to check whether the relative angular oscillation of each unit is gradually attenuated and whether the voltage level of the grid is within the acceptable range in the system, which means the stability of transient voltage and transient power angle need to be investigated.

The transient voltage acceptability needs to consider both the transient minimum voltage and the duration of the transient voltage sag (15 to 16). The United States west union power system, "reliability criteria for power grid operation" clearly states that the acceptable requirements for transient voltage sags are: Under N - 1 element failure case, transient voltage is lower than 80% rated voltage should not exceed 400 ms; N - 2 element failure case, transient voltage is lower than 80% rated voltage should not exceed 800 ms. In China, according to the simulation of actual voltage, the criterion of transient voltage stability is: after the fault is removed, the duration of bus voltage less than 0.75pu shall not exceed 1s. In addition, the transient stability of synchronous generator is expressed as power angle stability in the system. Because in the multi machine system, the relative value of the power angle to be meaningful, the power angle difference between any two units in the system reflects the relative positions between the unit rotors, furthermore, the power angle difference can be used to characterize the running state and stability level of the system. The maximum value of
angle difference between synchronous generators should not exceed 180 °, which is the premise of transient power angle stability.

1) checking requirements

The power grid operation modes are various, only the typical operating mode of the situation needs to be analyzed.

Static constraints checking requirements: (1) increasing wind power injection, control of wind farms and node voltage on the voltage rating of 5% ~ + 5%;(2) to control the entire network of busbar voltage at rated voltage - 5% ~ + 5%;(3) control of active power flow in 0 ~ 100 mw; Satisfy the constraint condition of the maximum power injection, that is, to the maximum power injection of wind farms under static constraint.

Checking requirements under dynamic constraints: using the wind speed disturbance and fault mode, the failure mode is the point of failure in wind farm grid-connected busbar, with the worst case of the fault form, which is three-phase short circuit, the fault line will be removed within 0.12s after three-phase short circuit grounding fault occurred in the wind farm grid-connected busbar.

Checking requirements under dynamic constraints: (1) Typical wind speed disturbance, the voltage and frequency of each node of the system also fluctuates with the wind speed, if the voltage deviation of each node is within ±10% of the rated value and the frequency deviation is within ± 0.5Hz, it is judged to be stable;(2) the failure mode, the largest generator power angle less than 180 degrees in the system, each node voltage is less than 0.75 within 1.0s, it is judged to be stable; Otherwise, the system is unstable.

2) Calculation steps

Step 1: choosing a grid-connected point, the initial injection power is 100 mw of the wind farm, through the power flow calculation, verify whether the system under this power meets the requirements with the condition of the static constraints;

Step 2: If it is satisfied, increasing the injection power of wind farms, repeating the steps 1; if there is any one exceeding the limit, the power with no exceeding the limit last time is taken as the maximum injection power of the wind farm which meets the static constraint condition;

Step 3: The wind farm power satisfying static constraints is used as the dynamic calibration of the initial power, power flow calculations first, and then through the transient stability calculation. the system under this power flow will be checked whether it meets the checking requirements with the condition of dynamic constraints, if it is satisfied, this power is the maximum injection power of the wind farm at the grid-connected points, and the calculation will be ended; If it is not satisfied, the wind electric injection power will be reduced unceasingly, and the transient stability of the system will be checked, until the system is stable, this power is the maximum injection power of the wind farm at the grid-connected points, and the calculation will be ended. The specific calculation process is shown in figure 2.
Simulation Analysis of Example

Priority Ranking of Wind Farm Site Selection

1. The index calculation

In PSASP simulation platform, it built 36 node system model, as shown in figure 3, the busbar of 220kV on load hub substation is respectively expressed as: node 9, node 16, node 18, node 19, node 20, node 21, node 23 and node 29.
A doubly fed wind turbine model is built on the PSASP simulation platform, and consider the PQ node, where \(Q=0, \cos \Phi = 1\). Only the active output is considered, and the 8 load 220kV bus nodes are used as wind farms grid-connected points. Under the condition of meeting the static constraint of the power grid, the wind power is injected into each grid-connected point is 110 mw, 120 mw, 130 mw, 140 mw and 150 mw. The voltage amplitude of the node is evaluated by power flow calculation, the distance of the grid voltage is calculated by formula (1). Grid voltage exceeding limit distance \(D\) and the corresponding grid losses are shown in figure 4 and 5.

![Figure 4. Grid voltage exceeding limit distance under different wind power.](image)

![Figure 5. Power loss under different wind power.](image)
From that, when a wind farm is injected with the same power, the D size is different at each grid-connected point, which indicates that the voltage stability level of power grid is affected by the location of wind farms. When the wind farm is connected to the nodes 29 and 16, the voltage stability of the grid is higher than that at node 9 and 23. With the increase of grid-connected wind power, D in each of the grid-connected point has increased, which indicates that the overall voltage operating level is further away from the target voltage level, the voltage level of the power grid has declined, the possibility of voltage exceeding limit is increased. Similarly, there is also the same trend in the change of power grid loss.

2. Priority ranking

The priority of each grid-connected points can be ranked by variation trend of index in figure 2 and 3. Priority is determined by counting, the numeric value represents the score of the index, the higher the score, the higher the priority. The indicators score up to eight, the minimum score is 1. The above results are sorted and then superimposed to obtain the final result, as shown in table 1.

To the large scale wind farm integration in specific power grid, the priority ranking of wind farms with different grid connected positions is from high to low: node 29, 18, 16, 21, 19, 20, 9 and node 23.

**Calculation of Maximum Injection Power in Wind Farm**

1. Static constraint checking

Under the condition of static constraint, the grid voltage amplitude of the grid connected points under the maximum injection power of the wind farm is shown in Figure 6.

![Figure 6](image-url)

**Figure 6.** The voltage amplitude of corresponding to the maximum input power under static constraint.
2. Check dynamic constraints

Dynamic constraint checking is performed on the basis of the maximum injection power of wind farm under the static bound from above calculation. Take node 19 as an example, dynamic constraint checking is performed on the basis of the acquired 158MW wind power. The fault point is located on the bus node 19, the fault line is removed in 0.12s after the fault of three-phase short circuit grounding happened. At this time, Transient voltage instability occurs in power grid, as shown in figure 7.

![Figure 7. Node voltage amplitude of transient voltage instability.](image)

In order to eliminate transient instability phenomenon, and decreases the node and the injection of wind power on the transient calibration, when the wind power reduction for 143 mw, there will be no voltage instability phenomena appear when shown in figure 8. Therefore, node 19 eventually maximum power injection of wind is 143 mw.

3. The calculation results

The maximum injection wind power at each grid-connected points is obtained under both static constraints and dynamic constraints, calculation results as shown in table 2 and figure 9.

![Figure 8. Node voltage amplitude of transient voltage stability.](image)

<table>
<thead>
<tr>
<th>Grid node</th>
<th>maximum power injection</th>
<th>Grid node</th>
<th>maximum power injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUS16</td>
<td>161MW</td>
<td>BUS18</td>
<td>143MW</td>
</tr>
<tr>
<td>BUS19</td>
<td>143MW</td>
<td>BUS20</td>
<td>159MW</td>
</tr>
<tr>
<td>BUS21</td>
<td>154MW</td>
<td>BUS29</td>
<td>161MW</td>
</tr>
<tr>
<td>BUS9</td>
<td>128MW</td>
<td>BUS23</td>
<td>105MW</td>
</tr>
</tbody>
</table>
Figure 9. Maximum power injection at different grid-connected point Conclusion through the analysis.

(1) In different operation mode, conventional constraints under the same conditions of generation units output, the maximum injection power of wind farms is different at different grid-connected points;

(2) The injected power of wind farm is affected by the electric distance between the wind farm and the system, the injection power from wind farm would be greater with the closer distance;

(3) The capacity of a wind farm connected to a large grid makes up a small proportion of the total installed capacity of the grid, therefore, the main problem that restricts the scale of the wind farm is the influence on the voltage of the power grid;

(4) The maximum injection power of the wind farms will be the same at different grid-connected points, but the voltage level of corresponding grid are different;

(5) The injection power of wind power is less affected by gust and gradual wind, it is greatly affected by system failure, are greatly influenced by the system failure, moreover, the maximum wind power value of the system obtained by sc method is greater than the power value obtained by the dynamic constraint method, which shows it is necessary to combine the analysis methods of static constraints and dynamic constraints in order to obtain the wind power values which can steady the system and the wind farm.

**Main Measures to Improve the Acceptance Capacity of Wind Power**

Measures to improve the wind power acceptance capacity of power grid can be mainly from the two aspects of power grid and wind power. For wind power, select reasonable types of wind turbines to improve the operation characteristics of wind power, so as to improve system stability; For power grid, the power supply structure can be improved, such as the new flexible regulation power, adding energy storage system and so on;

At present, with the actual power grid operation and technical level, mainly to solve the problem from two aspects: one is from the fan itself to improve the output characteristics of wind power generation system itself; The second is using energy storage technology to improve the output characteristics of wind farm, improve the operation stability of power grid and the acceptance capacity of wind power. It is very difficult to design the wind turbine itself to achieve the desired results, the technical requirements would be very high; therefore, energy storage technology can be used to achieve the goal. The energy storage system is used in wind power grid connected system to improve the capacity of wind power acceptance, mainly in the following three aspects:

Improve the quality of wind power supply and the acceptance capacity of wind power

Superconducting, super capacitor and flywheel with the ability of MS power dynamic regulation. Energy storage system can fast exchange active and reactive power between the system, which can suppress the fluctuation of wind farm output power, effectively improve power quality problems of voltage fluctuation, sag and flicker in the wind power grid-connected points and grid.

Enhancing system stability and increasing wind power acceptance

The active and reactive from the energy storage system is very helpful to improve the power balance of the wind power grid-connected system and to improve the operation stability of the system.
the energy storage system can quickly absorb excess energy during the grid fault, control the voltage at the terminals or access points. To ensure the wind turbines are not subjected to damage of overvoltage and over-current, and to enhance the LVRT capability of the wind turbines.

Optimize the economy of power grid, improve the capacity of wind power acceptance

The system must increase its original reserve capacity and even require additional balancing devices, which would reduce the economic efficiency of system operation. The energy storage system can largely reduce this cost, and realize the win-win situation of power grid and wind farm.

**Conclusion**

Based on the research of the wind power acceptable capacity, qualitative analysis of the factors influencing the power grid acceptance of wind power capacity the specific quantitative method is given to select access location and determine the maximum power injection of wind farms. Wind farms are usually in the end of the power grid, the grid space truss structure is weak, the trend of the distribution system will be changed after wind power access to the power grid, a drop in power grid voltage level, system transient stability would be changed and a series of problems, therefore, by using the method of combining static and dynamic constraints to determine the maximum power injection of wind farms. The analysis method in this research can provide a scientific analysis method to help the relevant departments decide the wind power development scale, also can be applied to power system planning and operation scheduling. The ideas adopted by the Institute can provide a reference for research of subsequent acceptance of large-scale wind power to the power grid.

**References**


