Research on Interaction and Coordination Control Technology of Wind Power and DC System of Receiving Grid

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Abstract. In this paper, an in-depth study on the interaction characteristics and coordinated control technologies of wind power and DC systems is carried out. This paper first defines the physical significance of the interaction between wind power and DC in the receiving grid. At the same time, an interaction factor that takes into account the strength of the wind and DC relative AC system and the relative impedance between them is established. Then the factors affecting the interaction between wind power and DC system are analyzed. Finally, the coordinated control strategy between the them is discussed. The North China Power Grid, which is connected by offshore wind power and Xitai DC, is used as an example. The results show that the smaller the electrical distance between wind power and DC system, the larger the scale of the two systems and the more obvious interaction between them.

1. Introduction
Driven by factors such as energy conservation, environmental protection, and price, the DC project of the receiving power grid was put into production successively, and the new energy represented by wind power and photovoltaics was merged into the grid to show a growing trend. The reactive voltage fluctuation of the original energy will affect the voltage of the DC converter station. At the same time, DC commutation failure and the blocking fault will also affect the operation of the wind farm. The interaction between the AC system, the DC system, and the green energy makes the operating characteristics of the power system extremely complicated.

At present, researches on the interaction between new energy and dc are mainly focused on wind power off-grid caused by AC and DC faults, transient stability characteristics and control strategy analysis of wind power or photovoltaic interconnection, and research on wind-fire ratio, etc [1-9]. Most of these studies focus on the interaction between the new energy centralized supply grid and onshore wind power. For the heavy-duty eastern and southeastern coastal receiving power grids, offshore wind power has become an important direction for future wind power development due to its stable resource conditions and close proximity to the load center.

Based on the concept of interaction between DCs in multi-input AC/DC systems, this paper defines the physical meaning of the influence of wind power and DC interaction on the receiving grid, and an interaction factor that takes into account the strength of the wind and DC relative AC system and the relative impedance between them is established. The key factors of the interaction between wind power and DC system are analyzed from the aspects of grid structure change, different proportion of wind and fire, wind power and DC input power. Based on the influence of different control modes of wind power and conventional power supply ratio, the coordinated control strategy between wind power and DC
system is discussed. The North China Power Grid, which is connected by offshore wind power and Xitai DC, serves as an example. This paper provides technical support for the wind power grid planning and acceptance capabilities of the receiving grid by quantitatively assessing the degree of interaction between wind power and DC.

2. Wind power and DC interaction factor

The mutual influence between DCs in a multi-feed AC/DC system is reflected by the node impedance matrix elements and the voltage change rate of each commutator busbar after being subjected to reactive disturbance \[^{10}\]. Similarly, the physical meaning of defining the interaction between the wind power and the DC of the receiving grid is: the reactive disturbance of wind farm $i$ is $\Delta Q_i$, the voltage change rate $\Delta U_j$ of the DC commutator busbar $j$ divided by the grid-connected bus voltage that dropped 1% of the wind farm $i$, which is the interaction factor $M_{IF, ij}$ of the wind farm to the DC commutator busbar voltage.

$$M_{IF, ij} = \frac{\Delta U_j}{1\% \Delta U_i} \quad (1)$$

Using the equivalent node impedance element to reflect the interaction with other DCs, refer to the multi-DC feed-in system to evaluate the mathematical concept of the interaction between DC and the derivation process. P-Q decoupling of the AC system:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{PS} & 0 \\ 0 & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta U / U \end{bmatrix} \quad (2)$$

Taking a two-input AC/DC system as an example, the following formula can be obtained:

$$\begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} \Delta U_1 / U_1 \\ \Delta U_2 / U_2 \end{bmatrix} \quad (3)$$

Assume $\Delta Q_2 = 0$, then there is:

$$\frac{\Delta U_2}{\Delta U_1} = -\frac{B_{21}}{B_{22}} = \frac{Z_{eq12}}{Z_{eq11}} \quad (4)$$

Substituting equation (4) into equation (1) gives the interaction of the wind farm to the DC bus voltage as:

$$M_{IF, ij} = \frac{\Delta U_j}{1\% \Delta U_i} = \left| \frac{Z_{ii}}{Z_{ij}} \right| \quad (5)$$

Where $Z_{ii}$ is the self-impedance of the grid-connected point of the wind farm $i$, and $Z_{ij}$ is the mutual impedance between the grid-connected point of the wind farm $i$ and the DC commutator busbar $j$.

The interaction between wind power and DC of the receiving power grid is not only related to the self-impedance and mutual impedance between the two, but also affected by the strength of the wind farm relative to the AC system and the strength of the DC site relative to the AC system. Therefore, the factor $M_{ij}$ defining the interaction between the wind power and the direct current of the receiving grid is:
Where \( K_i (K_i = P_i / S_i) \) is the short circuit ratio of the wind farm \( i \), \( P_i \) is the rated capacity of the wind farm, and \( S_i \) is the short circuit capacity of the connection point of the wind farm access system; \( E_j (E_j = S_{jac} - Q_e / P_{jdn}) \) is the effective short circuit ratio of the DC commutator bus \( j \), \( S_{jac} \) is the system short circuit capacity of the DC commutator bus, and \( P_{jdn} \) is the DC rated delivery capacity; \( Q_e \) is the reactive power of the reactive power compensation device such as the AC filter and the capacitance installed in the converter bus when the voltage of the AC bus of the converter station is the rated value; \( \alpha \) is the short circuit ratio, and \( \beta \) is the correction factor of the node impedance matrix element.

3. Factors affecting the interaction between wind power and DC

3.1. Typical AC and DC receiving system

A typical AC/DC receiving system is constructed, and the receiving system includes a conventional thermal power unit and a wind turbine. Based on the typical system, the coupling mechanism of new energy and dc operation is studied, which provides a basis for the research of a practical system. A typical system is constructed as follows:

The installed capacity of wind power is 248MW, and the unit types are wind turbines based on doubly-fed induction motors; thermal power unit installed capacity is 235MW; the active load of the receiving system is 700MW. A typical system receives power through an AC-DC line, where the DC rated transmission power is 200 MW, the AC input channel is a double-circuit line, and the AC input power is about 90 MW. Dc adopts constant power control, and wind turbine adopts constant power factor control, whose power factor is 1. The terminals of the AC line and the DC line are infinite systems.

Typical system wiring diagram is shown in Figure 1.
It can be known from equation (6) that the interaction between the wind power and the direct current of the receiving power grid is not only affected by the relative impedance between the two, but also related to the capacity of the DC relative AC system and the scale of the wind power relative to the AC system. It can be seen that the factors affecting the interaction between wind power and DC include: wind power output capacity, DC input power, wind power and thermal power configuration ratio, and grid structure.

In the above-mentioned typical AC-DC receiving system, five operating modes are constructed, as shown in Table 1. Firstly, the short-circuit capacity of the DC-receiver busbar and the short-circuit capacity of the access point of the wind farm connected to the main network are calculated separately under different operation modes. Then, according to the wind power output capacity, the short-circuit capacity of the wind farm, the DC input power, the reactive power compensation capacity, and the short-circuit capacity of the DC commutation bus, the wind farm short-circuit ratio $K_i$ and the DC commutation bus $j$ effective short-circuit ratio $E_j$ are calculated. Finally, the calculated $K_i$, $E_j$, the mutual impedance $Z_{ij}$ between the wind power grid-connected bus and the DC converter bus and the wind power grid-connected bus self-impedance $Z_{ii}$ are substituted into equation (6) (here, $\alpha = \beta = 1$).

The wind power and DC interaction factor $M_{ij}$ are obtained. The results are shown in Table 2.

| Mode | Thermal power output capacity (MW) | Wind power output capacity (MW) | DC receiving power (MW) | Grid structure change |
|------|----------------------------------|-------------------------------|------------------------|----------------------|
| One  | 235                              | 183                           | 200                    | ——                   |
| Two  | 139                              | 279                           | 200                    | ——                   |
| Three| 139                              | 279                           | 200                    | There is a line maintenance for the bus 2 to bus A lines. |
| Four | 139                              | 279                           | 290                    | ——                   |
| Five | 139                              | 279                           | 290                    | The lines from bus 2 to bus A is increased to four lines |

| Mode | Short circuit capacity (MVA) | Converter station | Connecting point | $K_i$ | $E_j$ | $Z_{ij}$ | $Z_{ii}$ | $M_{ij}$ |
|------|-------------------------------|-------------------|-----------------|-------|-------|---------|---------|---------|
| One  | 956                           | 2226              | 2226            | 0.08221 | 4.28000 | 0.03033 | 0.04702 | 1.24%   |
| Two  | 957                           | 2252              | 2252            | 0.12389 | 4.28500 | 0.02998 | 0.04648 | 1.86%   |
| Three| 859                           | 2136              | 2136            | 0.13062 | 3.79500 | 0.02437 | 0.04900 | 1.71%   |
| Four | 957                           | 2252              | 2252            | 0.12389 | 2.81720 | 0.02998 | 0.04648 | 2.84%   |
| Five | 1055                          | 2356              | 2356            | 0.11842 | 3.15520 | 0.03451 | 0.04444 | 2.92%   |

It can be seen from the calculation results:

- As the scale of wind power increases, the short-circuit ratio of wind farms increases, and the interaction factor also increases.
- As the DC input power increases, the effective short circuit ratio of the DC converter busbar is greatly reduced, and the interaction factor increases.
- The electrical distance between the wind farm and the DC drop point increases, the interaction factor decreases; the electrical distance between the wind farm and the DC drop point is shortened, and the interaction factor is increased.
As the proportion of wind power and thermal power increases, the interactive impact indicator also increases.

3.2. Actual AC and DC receiving system

Taking Jiangsu as an example, wind power clusters along the coast of northern Jiangsu, its inherent stochastic volatility, complex nonlinearity of power electronic topologies and time-variation of multiple time scales make the ultra-high ratio wind farm has a significant impact on the power angle stability, voltage stability and frequency stability of the power grid\textsuperscript{[12-17]}. At the same time, Xitai DC 10000MW is layered into the northern Jiangsu area, and the voltage support capability of the receiving end has a great influence on the failure of DC commutation and the stability of the system after DC blocking. Therefore, it is necessary to study the interaction between offshore wind power centralized access and Xitai DC layered access in northern Jiangsu.

The offshore wind power in northern Jiangsu is clustered in Yancheng and Nantong, with a grid-connected capacity of 7,200 MW, showing a wide range of distributed distribution. The access points are 220kV, distributed in Dongling, Longhai, Huaqi, Dongtai, Guohua, Longyuan, Ludong, Dafeng and Binhai 220kV bus, as showing in Figure 2.

\[
M_{wjd\text{c}} = \alpha \frac{K_{iw}}{E_{jdc}} \times \beta \frac{|Z_{iwjd\text{c}}|}{|Z_{iwiw}|} \quad (7)
\]

According to formula (6), the interaction coefficient \(M_{wjd\text{c}}\) of the offshore wind power reactive power fluctuation to the DC inverter side AC bus voltage is obtained:

| Offshore wind to DC | Xitai DC (high end) | Xitai DC (low end) |
|---------------------|---------------------|---------------------|
| Yancheng Wind Power | Binhai 0.00103      | 0.00048             |
|                     | Dongtai 0.00130     | 0.00045             |
|                     | Guohua 0.00259      | 0.00090             |

Figure 2. North Jiangsu Offshore Wind Power and Xitai DC

Here, \(\alpha = \beta = 1\) is taken to calculate the interaction factor of the offshore wind power in northern Jiangsu on the Xitai DC. The results are shown in Table 3.
Similarly, according to equation (6), the voltage interaction factor \( M_{dcjw} \) of reactive power fluctuation at dc landing point on offshore wind power gathering station can be obtained:

\[
M_{dcjw} = \frac{K_{jw}}{E_{idc}} \times \frac{\omega_{idc,jw}}{[\omega_{idc}]} \quad (8)
\]

Here, take \( \alpha = \beta = 1 \) and calculate the interaction factor of Xitai DC to the offshore wind power in northern Jiangsu. The results are shown in Table 4.

Table 4. Interaction factor of Xitai DC to the offshore wind power in northern Jiangsu.

| DC to offshore wind | Xitai DC (high end) | Xitai DC (low end) |
|--------------------|---------------------|--------------------|
| Yancheng Wind Power | Binhai 0.00295 0.00144 | Donghai 0.00730 0.00268 |
|                    | Guohua 0.00923 0.00338 | Dafeng 0.00460 0.00165 |
|                    | Longyuan 0.00460 0.00165 | Longhai 0.00298 0.00149 |
| Nantong Wing Power | Dongling 0.00308 0.00155 | Huaqi 0.00308 0.00169 |

It can be seen from the above calculation that the north Jiangsu voltage support capability is strong, the offshore wind farm short-circuit ratio is small, and the effective short-circuit ratio of the high-low end of the Xitai DC inverter side is large. At the same time, since the wind farm is connected to the 220kV bus, the electrical distance from the DC drop point is far, and the mutual impedance between the wind power connected to the main bus and the DC receiving bus is small. Therefore, the interaction factors between the offshore wind power of the North Jiangsu and the Xitai DC are less than 1%, indicating that the interaction between the offshore wind power in North Jiangsu and the Xitai DC is minimal.

- Taking the gradual wind disturbance of Guohua Wind Farm as an example, the voltage fluctuation of the grid-connected busbar of Guohua Wind Farm and Xitai High/Low-end converter bus is simulated, as shown in Figure 3–5 and Table 5.
Figure 3. Guohua Wind Farm Grid-connected Bus Voltage Variation Curve.

Figure 4. Xitai high-end converter bus voltage curve.

Figure 5. Xitai low-end converter bus voltage curve.

Table 5. Guohua Wind Farm's gradual wind disturbance, the grid-connected busbar of Guohua Wind Farm, Xitai DC high and low end commutation bus voltage changes.

| Busbar                  | Initial voltage (p.u.) | Recovery voltage (p.u.) | Voltage change rate |
|-------------------------|------------------------|-------------------------|---------------------|
| Guohua Wind Farm        | 0.9618                 | 0.9595                  | 0.00239             |
| Xitai high-end          | 0.9864                 | 0.9860                  | 0.00041             |
| Xitai low-end           | 0.9930                 | 0.9929                  | 0.00010             |

The calculation values and simulation values of the interaction factors of Guohua Wind Farm on the high and low ends of Xitai DC are shown in Table 6. It can be seen that the gradual wind disturbance is applied to Guohua Wind Farm, which affects the voltage fluctuation of the grid-connected busbar of the wind farm, and thus affects the voltage change of the high- and low-end converter bus of Xitai DC. The value obtained from the simulation of the physical meaning of the wind power and the DC interaction factor m is close to the value calculated by the equation (7).
Taking Xitai DC high/lowside exit capacitor as an example, simulate the voltage fluctuation of the Xitai high/low-end converter bus and Guohua wind farm grid-connected bus, and calculate the interaction factor of high and low ends of the Xitai DC to Guohua Wind Farm according to formula (8). The results are shown in Table 7.

Table 7. Interaction factor of high and low ends of the Xitai DC to Guohua Wind Farm.

| Interaction factor | Calculated value | Simulation value |
|--------------------|------------------|------------------|
| Interaction factor of high end of the Xitai DC to Guohua Wind Farm. | 0.00923 | 0.00502 |
| Interaction factor of low end of the Xitai DC to Guohua Wind Farm. | 0.00338 | 0.00206 |

Similarly, the operation of the high and low side exit capacitors of the Xitai DC affects the voltage fluctuation of the busbar of the converter station, which in turn affects the voltage variation of the grid-connected bus of the Guohua wind farm. The value obtained from the simulation of the physical meaning of the wind power and DC interaction factor $M_{ij}$ is close to the value calculated by equation (8).

4. Coordinated control measures for wind power and DC systems

4.1. Influence of different control modes of wind power on DC lines

The wind turbine reactive control mode includes constant power factor mode and constant voltage control mode. When the wind turbine is running in the constant voltage control mode, it will inject some reactive power into the system during the short circuit fault, but only play a role in the local voltage support in the near region. With the integration of the North Jiangsu wind power into the 220kV bus, the electrical distance from the Xitai DC receiving station is far away. Therefore, the wind turbine has little effect on reducing the number of Xitai DC commutation failure in the constant voltage control mode.

The short-circuit capacity of the Xitai DC converter busbar can be affected by changing the boot mode, thereby affecting the failure of the Xitai DC commutation failure caused by the near-field AC fault.

Take the three-phase permanent N-1 fault on the Longxing side of the Longxing-Binxiang line at 220kV as an example. The wind turbine operates in constant power factor mode (power factor is 1). When the wind turbine replaces the thermal power unit and the short-circuit capacity of the high-end side converter bus of Xitai DC is less than 33500 MVA, the commutation failure of the Xitai DC after the three-phase permanent N-1 fault on the Longxing side will occur, as shown in Table 8.

Table 8. Xitai DC commutation failure under different short-circuit capacity.

| Mode | Xitai high-end short circuit capacity (MVA) | Number of commutation failures |
|------|--------------------------------------------|-------------------------------|
| Original mode | 33268 | 1 |
| Binhai wind farm reduced power of 200MW, Yancheng 220kV thermal power increased output | 33372 | 1 |
| Binhai wind farm reduced power of 200MW, Yancheng 500kV thermal power increased output | 33500 | 0 |
4.2. Influence of different proportions of wind power thermal power on DC lines

To establish steady-state operating conditions for DC and wind power, the system needs to provide a certain short-circuit capacity. At the same time, it is necessary to provide the necessary voltage support from the system to recover stable operation after the fault. The near-field thermal power unit can provide the short-circuit capacity and voltage support required for stable operation of the system.

After the wind power is connected, if the short-circuit capacity caused by the local thermal power supply is turned off, the DC commutation failure will be worse under AC failure. Taking Xitai DC near-area AC outlet switch rejection action as an example, compare the system stability under four different wind power thermal ratios, wind power off-state and Xitai DC commutation failure, as shown in Table 9.

Table 9. The stability of the switch refused to operate under different wind power and thermal power ratios.

| Xitai DC high-end short circuit capacity (MVA) | Operation mode | Stability | Wind farm situation | Commutation failure |
|-----------------------------------------------|----------------|-----------|---------------------|---------------------|
| 33937 Wind power normal operation / Yancheng thermal power all work | The main network is stable, Tianwan Nuclear Power Unit is out of step | Wind turbine without off-grid | 2 |
| 33268 Normal operation of wind turbine/ Yancheng each thermal power units only turn on one | The main network is stable, Tianwan Nuclear Power Unit is out of step | Wind turbine without off-grid | 3 |
| 33021 Wind turbine exits operation | The main network is stable, Tianwan Nuclear Power Unit is out of step | Wind turbine without off-grid | 3 |
| 32260 Normal operation of wind turbine/ Yancheng thermal power all down | The main network is stable, Tianwan Nuclear Power Unit is out of step | Wind turbine without off-grid | 3 |

When the proportion of wind power and thermal power in Yancheng area increases to the short-circuit capacity of Xitai high-end converter busbar less than 33937MVA, the number of failures of Xitai DC commutation failure will be increased from 2 to 3 under the three-phase short circuit and single-phase switch rejection action.

5. Conclusion

- The interaction factors between wind power and dc are established, which comprehensively consider the AC system strength of wind power grid connection and DC access point, and the relative impedance between wind power grid connection bus and DC converter bus. The smaller the electrical distance between the wind power and the DC system, the larger the scale of the two, the more obvious the interaction between the two.
- The factors influencing the interaction between wind power and DC include wind power output capacity, DC input power, different proportions of wind power and thermal power, and changes in grid structure.
- It reveals the relationship between wind power, thermal power and direct current interaction. In order to reduce the interaction between reactive power fluctuation between wind power and direct current, it is necessary to coordinate and control the direct current transmission power and wind power grid-connected capacity; the increase in DC transmission power and wind power grid-connected capacity depends on the increase in the short-circuit capacity of the access.
point, that is, the increase of the number of thermal power units and the strengthening of the network structure.

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