Analysis of Offshore Wind Power Integration

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Abstract. In recent years, global energy and environmental problems have become increasingly prominent, and wind power has entered a period of rapid development. At the same time, offshore wind power integration is also facing many challenges and problems. Based on the analysis and research of offshore wind power integration, this paper introduces the technologies of offshore wind power integration such as HVAC, LCC-HVDC and VSC-HVDC, and discusses the impact of large-scale offshore wind power on power grid, interaction with UHVDC, voltage ride through and harmonic vibration of offshore wind power, and the impact of large-scale wind power integration on power grid and power quality problems are studied. The research and breakthrough of these problems will greatly benefit the development of offshore wind power industry.

1. Introduction

Compared with inland wind power, offshore wind power has the advantages of high wind speed, low wind shear, low turbulence, high output and long service life. In recent years, with the increasingly prominent global energy and environmental problems, especially the threat of global warming, wind power has entered a period of rapid development. In 2018, China's offshore wind power added about 1.8 million kilowatts, with a cumulative installed capacity of 4.6 million kilowatts, less than that of the UK and Germany, ranking third in the world. More than 8 million kilowatts of offshore wind power projects will be completed by 2020. At the same time, the integration of offshore wind power and power grid is facing many challenges and problems.

For the problem of offshore wind power integration, the VSC-HVDC wind power integration model is established in reference [1], the power quality problem under fluctuating wind speed is studied, and a reasonable filtering scheme is proposed. In reference [2], the grid connected technology and grid connected collection mode of offshore wind power are compared and studied respectively. In reference [3 ~ 6], the key factors of interaction between UHVDC System and offshore wind power, key electrical equipment and grid connection technology of offshore wind power flexible DC transmission project, parallel resonance of long-distance fast power transmission, and voltage ride through of large-scale offshore wind farm are discussed. Literature [7] summarizes the impact of large-scale offshore wind power access on the power grid and the countermeasures. Literature [8 ~ 9] introduces the current situation and development direction of offshore wind power generation technology from the aspects of wind power converter, wind turbine support technology and wind turbine design.

In this paper, the offshore wind power through the high voltage AC transmission (HVAC), traditional DC transmission (LCC-HVDC) and flexible DC transmission (VSC-HVDC) and other different grid connected ways are studied, and the advantages and disadvantages of each way are...
compared. The paper summarizes the influence of large-scale offshore wind power on power grid, the interaction with UHVDC, voltage crossing and offshore wind power resonance. In the future, the research of these problems and the breakthrough in standards and technology will greatly promote the development of offshore wind power industry.

2. Offshore wind power integration technology
Large-scale offshore wind power integration will bring voltage fluctuation, power flow uncertainty and many other problems to the power system, especially when it is connected to the power grid with weak grid structure, the security and stability of the system will be severely tested [2].

2.1. Integration into the power grid via HVAC
The electrical system of offshore wind power grid connected by HVAC mainly includes wind turbine group, medium voltage AC collector grid, offshore substation, high voltage AC transmission line and onshore substation. The voltage level of the AC power grid of offshore wind farms is usually 33-36kv. The offshore substation will further boost the voltage to 110kV or 220kV, and then connect it to the grid through cables.

![Figure 1. Schematic diagram of offshore wind power based on HVAC grid connection](image1)

The advantages of offshore wind power grid connected by HVAC are simple structure and low project cost. There are three main disadvantages:
- The transmission distance is limited due to the large ground capacitance. In order to improve the transmission capacity, it is usually necessary to install reactive power compensation device in offshore substation or onshore substation.
- It is greatly affected by the power grid. When using HVAC transmission, the offshore wind farm and the onshore power grid belong to the synchronous power grid. When the onshore power grid is disturbed due to fault, the offshore wind farm will be greatly affected, and even the wind farm will be off grid when it is serious.
- The transmission loss is high. When the transmission active power is constant, the loss is higher than that of DC transmission. And with the increase of transmission distance, the power loss increases faster than that of DC transmission.

2.2. Integration into the power grid via LCC-HVDC
Similar to the HVAC grid connection, the wind turbine group with LCC-HVDC grid connection also needs to go through the boost process. After that, the system connects to an LCC rectifier station, and then transmits the power to the onshore LCC inverter station through DC cable, and finally connected to the power grid.

![Figure 2. Schematic diagram of offshore wind power based on LCC-HVDC grid connection](image2)
The advantages of LCC-HVDC: compared with HVAC, LCC-HVDC has larger transmission capacity. Using DC transmission, the capacitance charging effect of cable can be almost ignored, so the transmission distance can be unlimited; the transmission loss is smaller than that of HVAC; the wind farm and the shore power grid operate asynchronously, the fault of the shore power grid has less impact on the offshore wind farm, and LCC-HVDC plays a role of fault isolation.

The disadvantages of LCC-HVDC offshore wind power integration technology are as follows:
- There is a risk of commutation failure. When a serious AC fault occurs on the inverter side of LCC-HVDC, commutation failure will occur in the inverter station. In this case, it is necessary to design the corresponding wind farm fault ride through method.
- Large offshore platforms need to be built. LCC converter station has a large volume and needs to install filters and reactive power compensation devices, which occupies a large area and needs to build a large offshore platform. With the increase of offshore distance of wind farm, the construction cost of offshore platform will further increase.
- The system has no black start capability. Because LCC can not supply power to the passive network, additional generators need to be installed in the offshore substation before the whole grid connected system is started.

2.3. Integration into the power grid via VSC-HVDC

Flexible direct current transmission (VSC-HVDC) is based on voltage source converter.

The advantages are:
- Large transmission capacity and unlimited transmission distance.
- The transmission loss is smaller than that of HVAC, but slightly higher than that of LCC-HVDC.
- The wind farm operates asynchronously with the shore power grid.
- Since VSC-HVDC can control active power and reactive power independently, no additional reactive power compensation device is needed.
- IGBT is used as switching device, which eliminates the problem of commutation failure.
- It can supply power to the passive network and has black start capability. The system does not need to install auxiliary power supply in the offshore substation during the start-up process.

The disadvantages are:
- Due to the need of VSC rectifier, it is larger than the offshore platform of HVAC grid connected technology. But it doesn't need reactive power compensation device and auxiliary power supply, which is smaller than LCC-HVDC offshore platform.
- The VSC converter station uses more expensive IGBT devices, which is more expensive than the LCC converter station using thyristors.

As mentioned above, HVDC is mainly used for offshore wind power integration, not for long-distance offshore wind power integration. LCC-HVDC and VSC-HVDC technologies can be used for long-distance large-scale offshore wind power integration. Compared with LCC-HVDC, VSC-HVDC has higher control flexibility, strong anti-interference ability and black start ability, which is more suitable for long-distance large-scale offshore wind power integration. Therefore, VSC-HVDC technology is used in all long-distance offshore wind power integration projects in the world[4].
3. Problems of offshore wind power integration

Large scale offshore wind power integration will bring many problems to the system, such as the quality of live energy, and make the stability and safety of the system worse.

3.1. Impact of large scale offshore wind power integration on Power Grid

3.1.1. Impact on Power Grid

- System frequency modulation

  Wind power output has randomness, intermittence and fluctuation, and the prediction of wind power output is more difficult than conventional power supply. According to the existing wind power operation data, the synchronous rate of offshore wind power is higher, and the power fluctuation is more significant than that on land. Large scale offshore wind power is connected to the terminal weak power grid, which weakens the primary frequency regulation capability of the power grid. If a large area of off grid accident occurs, the impact on the system frequency fluctuation can not be ignored. In addition, due to the uncontrollable power characteristics of wind turbines, wind turbines basically do not participate in the system frequency regulation, and the frequency regulation is still undertaken by the conventional power supply. When large-scale offshore wind power is connected and operated, more reserve capacity for frequency regulation is required, which, to a certain extent, occupies the power generation space of other power sources.

- Load regulating

  Load regulating is one of the main contradictions restricting the large-scale integration of wind power in China. According to the existing wind power operation data, wind power in most areas has obvious anti peak regulation characteristics. Large scale offshore wind power integration will lead to the increase of peak valley difference of power grid. With the increase of offshore wind power installed capacity, the randomness and volatility of wind power output objectively require the power grid to reserve the peak shaving capacity of other power sources, which also brings great challenges to power grid dispatching, operation control and mode arrangement.

- System voltage regulation

  With the increasing proportion of wind power installed capacity in the generation side, the impact of its output instability on the power grid is gradually increasing. When the wind power output is high, the line reactive power loss and wind farm reactive power demand will increase. The lack of reactive power in the power grid will affect the voltage stability, reduce the voltage of remote end users, and greatly affect the power supply quality and power grid security.

3.1.2. Power quality problems

Power quality after grid connection is one of the focuses of current research, which is also the key to large-scale application of offshore wind power [1].

- Voltage flicker

  In the process of continuous operation of offshore wind farm, due to the influence of wind shear, variability of offshore wind speed and other factors, the output power of offshore wind turbine fluctuates, and the frequency range of voltage flicker is the frequency range, which causes the voltage fluctuation of wind turbine side and grid connection point. When the fluctuation range is large, it may even cause perceptible flicker [1]. The formula for calculating the total flicker generated by the common connection point of multiple fans in continuous operation is shown in (1):

\[
P_{\Sigma} = \sum_{i=1}^{N} \left( \sum_{k=1}^{S_k} c_i(\phi_k, \nu_k) S_{n,i} \right)^2
\]

Among them: \( S_{n,i} \) represents the rated apparent power of a single wind turbine; \( S_k \) represents the short-circuit capacity of the common connection point; \( c_i(\phi_k, \nu_k) \) represents the flicker coefficient of a
single wind turbine; $\phi$ represents the network impedance angle of the common connection point; $\nu$ represents the annual average wind speed of the hub height of the wind turbine; $N_w$ represents the number of wind turbines connected to the common connection point.

- **Voltage deviation**
  
  During the normal operation of power system, the voltage of each node in the system will change, resulting in the actual voltage deviation from the rated voltage, which is called voltage deviation. The voltage deviation of offshore wind farm should not exceed 10% of the nominal voltage. The voltage deviation can be calculated by the following formula. In the above formula, Where $U$ is the actual voltage and $U_N$ is the nominal grid voltage.

$$\Delta U = \frac{U - U_N}{U_N} \times 100\%$$

- **Harmonic**
  
  In the power system, due to the existence of nonlinear devices such as power electronic equipment, harmonics will be generated. The harmonic generated by the generator in doubly fed induction wind turbine can be ignored, and the power electronic equipment is the real harmonic source. After the operation of the offshore wind farm, the converter will always operate. Therefore, the offshore wind farm will cause harmonic problems. Voltage harmonic distortion rate is used to measure the degree of voltage waveform distortion. The voltage harmonic distortion rate represents the percentage of the ratio of RMS value of each harmonic voltage to RMS value of fundamental voltage:

$$V_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1}$$

$V_1$ is the effective value of fundamental voltage, $V_n$ is the effective value of $n$th harmonic voltage.

### 3.2. Interaction between offshore wind power and UHVDC

The influence of offshore wind farm on UHVDC receiving end grid is reflected in the voltage aspect, which affects the voltage of wind power parallel point through the reactive power support characteristics of wind turbine and dynamic reactive power characteristics after fault, and then affects the AC bus voltage at DC inverter side \[3\]. The key factors of interaction between UHVDC and offshore wind power are as follows:

- **Effective short circuit ratio of UHVDC**
  
  With the access of UHVDC in the receiving end system, the start-up of thermal power units will be reduced, the moment of inertia of the system will be reduced, and the transient voltage of offshore wind turbines will increase under the common disturbance forms such as DC restart, commutation failure and blocking. The impact of DC system on offshore wind power largely depends on the strength of AC system at receiving end relative to DC transmission capacity. When reactive power compensation equipment is considered, the concept of effective short circuit ratio is usually used to measure. The larger the index is, the smaller the impact on AC or offshore wind farm caused by DC input or operation state change.

$$E_{SCR} = \frac{S_a - Q}{P_{dn}}$$

Among them: $S_a$ is the system short-circuit capacity of DC converter bus; $P_{dn}$ is the rated transmission capacity of DC; $Q$ is the reactive power output of AC filter, capacitor and other reactive power compensation equipment installed on converter bus under rated state.

- **Short circuit ratio of offshore wind power**
With the increase of offshore wind power access capacity, the degree of voltage fluctuation caused by wind power fluctuation in extreme bad weather will increase, which will cause great disturbance to the power grid and increase the impact on DC operation. The influence of wind farm on AC system and AC bus voltage at DC inverter side is mainly related to the output level of wind farm and the ability to provide reactive power[3]:

$$K_w = \frac{P_w}{S_w}$$

Where: $P_w$ is the rated capacity of the wind farm; $S_w$ is the short-circuit capacity of the connection point with the wind farm access system. The size of $K_w$ determines the strength of the connection between the node and the system, and reflects the sensitivity of the voltage of the wind farm bus to the change of the injected power of the wind farm. The smaller the $K_w$ is, the stronger the ability of AC system on DC inverter side to resist wind power random variation disturbance is. Therefore, the size of $K_w$ reflects the impact of reactive power fluctuation of wind farm on DC operation of receiving end grid to a certain extent.

3.3. Voltage ride through
With the increase of the number and capacity of fans connected to the grid, the wind power permeability is constantly improving. In case of grid failure, the power loss of the grid will be caused by the fan disconnection operation, which will cause secondary impact on the grid, damage the stability of the power system, and even lead to grid collapse. In order to ensure the reliability of power supply, it is required that the fan should not be disconnected from the network for a period of time when the power grid fails, that is, fault crossing, including low voltage ride through (LVRT), high voltage ride through (HVRT) and frequency crossing [6].

In addition to short-circuit fault, the power grid is prone to voltage drop, but also voltage surge fault, such as emergency load shedding, single-phase reclosing, large capacitor access and so on, will cause the voltage rise of the parallel point. In addition, due to the fact that the wind turbines connected to the grid generally do not have the LVRT capability or the LVRT capability is insufficient when the fault occurs, the voltage of the parallel point will rise after the LVRT failure and disconnection. However, the increase of voltage at the merging point will lead to more wind turbines off grid due to lack of HVRT capability, which will cause chain reaction. The effect of submarine cable to ground capacitance and the transient charging and discharging of transformer and submarine cable during the opening operation of circuit breaker will cause the overvoltage problem of offshore wind farm.

At present, the research on HVRT technology of wind turbine in China mainly focuses on the control strategy and modeling of electromagnetic transient characteristics of single wind turbine,

There are few researches on the fault ride through characteristics of wind farms, especially offshore wind farms. Especially offshore wind farms. There are still some problems to be solved, such as the generation mechanism of voltage surge, the characteristics of fault occurrence and the HVRT method:

- The cause of voltage surge is not clear enough. The model based on electromagnetic transient simulation program can realize the phenomenon of voltage surge, but there is lack of enough actual data to explain the cause of voltage surge.
- The standard of HVRT is not accurate enough. There is no relevant HVRT standard in China.
- The new HVRT method needs to break through. With the rapid development of power electronic technology and control technology, it is one of the key research directions in the future to carry out the topology transformation of rotor side converter or grid side converter, or to improve the control method, or to completely realize the HVRT technology.

3.4. Resonance problem of remote power transmission
Due to the small influence of power grid, offshore wind farms may avoid the interruption of power supply by collecting lines (submarine cables). However, due to the limitation of going to sea caused by
climate, wind turbines are often inaccessible. No matter what kind of power transmission mode is adopted, the parallel ferromagnetic resonance of the main transformer cannot be completely avoided. But the resonance interval is not enough to cause serious harm to the transformer.

4. Conclusion

Based on the analysis and research of offshore wind power integration, this paper compares and introduces three kinds of offshore wind power integration technologies, such as HVAC, LCC-HVDC and VSC-HVDC. Then, the impact of large-scale offshore wind power access on power grid, interaction with UHVDC, voltage ride through and offshore wind power resonance are studied.

For a series of problems caused by offshore wind power integration, this paper only studies the more frequent aspects, not comprehensive. Some indicators have not yet clearly defined national standards and specific calculation methods. With the progress of research and the introduction of standards, the problems related to offshore wind power grid connection will be solved scientifically and accurately in the future, which will greatly benefit the development of offshore wind power industry.

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