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Transient Protection Schemes for Transmission Lines Used in Offshore Wind Farm: A State-of-the-Art Review

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The weak feeder and high harmonic characteristics of wind farms connected to the grid have an impact on the safe operation of the system, especially on the action selectivity and reliability of the traditional work-frequency quantity protection, which makes the transient protection of wind farms become a hot direction of wind power development and research. In this article, the key technologies of transient protection for offshore wind farm transmission lines are reviewed, including the analysis of the fault characteristics of wind farm transmission lines based on two types of wind turbines (i.e., doubly fed asynchronous wind turbines and direct-drive permanent magnet synchronous generators), while the comparison with the characteristics of ground faults and short-circuit faults in traditional synchronous power systems as well as the current status of research on transient protection for offshore wind farm transmission lines, upon which the protection of wind farm transmission lines is also discussed.

Keywords: offshore wind farms, feeder lines, transient protection, fault transient characteristics, wind power

INTRODUCTION

With the continuous advancement of renewable energy generation technology, wind power generation occupies a vital position with its mature technology and other privileges (O'Shaughnessy et al., 2021; Telukunta et al., 2017; Wang et al., 2022). Offshore wind farms are mainly connected to the grid by means of centralized access, while the random, intermittent, and fluctuating nature of wind power after grid connection can have an impact on the safe operation of the system with the most significant impact on relay protection (Gao et al., 2021). The fault characteristics of wind farms connected to the grid are more different than those of traditional power grids (Bi et al., 2014; Prasad et al., 2020; George and Ashok, 2021), which makes the traditional frequency quantity protection in wind farm grid-connected systems have problems such as misoperation and sensitivity degradation (Jia et al., 2018; Xu et al., 2021). In addition, related research points out that the data collected as the main protection of transmission lines in longitudinal differential protection, distance protection, and directional longitudinal protection are generally frequency voltage and current, while the phase extraction of frequency quantities based on the Fourier algorithm is no longer accurate (Swetapadma and Yadav, 2018; Guillen et al., 2020). The literature (Wang, 2016) shows through theoretical analysis and simulation that the protection based on the distance protection and the directional component of the positive sequence fault component is no longer applicable to large-scale wind farm transmission lines.

In addition, offshore wind farm transmission lines are high-voltage transmission lines. If it is not cut off in time after a fault, the system will operate with fault for a long time, which may lead to the expansion of the accident. Therefore, it must be quickly and reliably removed. Also, after the fault, the high-frequency transient volume contains rich information on the characteristics of the fault, while based on the transient volume of the protection, the required time window is short, good quick action. Thus, the study of transient protection schemes is the current trend in relay protection.

This article first introduces the main transient characteristics of wind farm delivery lines based on doubly fed wind turbines and direct-drive permanent magnet wind turbines after a fault, which summarizes the selection principle of transient protection for wind farm delivery lines. Moreover, it summarizes the current status of research on wind farm delivery lines based on transient protection, which analyses the characteristics of transient protection for wind farm lines. Finally, suggestions are made for future research on the transient protection of large-scale wind farm transmission lines.

FAULT TRANSIENT CHARACTERISTICS OF WIND FARM TRANSMISSION LINES

The intermittent and randomness of wind power make changes in its internal control system that have an impact on the fault characteristics (Li et al., 2018a; Alejandro and Joaquin, 2019), while the analysis of the transient characteristics after a fault is the basis for the study of transient quantity protection in wind power systems. The main renewable energy sources used in the market can be divided into doubly fed sources and inverter sources represented by permanent magnet direct-drive wind turbines (Haj-Ahmed et al., 2018). In particular, the following will analyze the transient characteristics after a transmission line fault of wind farms based on these two types of wind turbines.

Wind Farms Based on Doubly Fed Asynchronous Wind Turbines

Doubly fed asynchronous wind turbines do not have a separate excitation winding compared to conventional synchronous generators. Studies have shown (Chen, 2019) that the transient potential of a doubly fed wind turbine remains basically unchanged for a relatively short period of time after a fault, i.e., there is inertia in the transient potential of a doubly fed wind turbine for a short period of time after a fault, while the rotor magnetic chain satisfies the principle of magnetic chain conservation for a short period of time after a fault whose changes are slow. In practice, crowbar protection is usually put in after a delay of a few milliseconds (generally more than 5 ms) (Zheng et al., 2014), upon which after the fault is regulated by the doubly fed fan controller, there will be harmonics in the transient current after the fault as well as the waveform pattern is more complex (Li et al., 2020), while the duration of the transient equivalent potential inertia will be very short. Considering the delay of the rotor side converter of the doubly fed fan and the response time of the control system, it can be assumed that there is inertia in the doubly fed fan transient potential for 2 ms after the fault.

Wind Farms Based on Direct-Drive Permanent Magnet Synchronous Generators

Compared to doubly fed wind turbines, permanent magnet synchronous generators do not have a speed-boosting gearbox, so it avoids many adverse effects and improves the stability of the system. The short-circuit current characteristics of inverter-containing power supplies differ significantly from those of conventional synchronous generators (Biswas and Nayak, 2021; Dakic et al., 2021; Liu et al., 2021). After the three-phase fault occurs, the fault phase current presents the characteristics of superposition of non-frequency attenuated sine wave and non-frequency sine wave with volatility. The transient characteristics at the initial stage of the fault are related to the internal control after grid connection, while the fault characteristics after grid connection are mainly affected by the capacity of the wind farm connected to the power grid (Li et al., 2019; Zeng et al., 2019). Multiple resonant frequencies may appear in the AC network of an offshore wind farm, which results in the increase of harmonic loss of the power grid, so as to affect the transient characteristics after a system failure (Wang et al., 2020). When studying the influence of the characteristics of direct-drive wind turbines on the system transient process after connection to the grid, the transient model of direct-drive wind turbines is considered too complex with high order (Xu et al., 2015). The transient model of direct-drive wind turbines is generally simplified (Kunjumuhammed et al., 2017), while the converter is replaced by a controlled source to reduce the complexity of the analysis process due to reflecting the output characteristics of wind turbines more accurately.

In addition, for offshore wind power via the flexible straight converter station of the grid-connected system, the wind farm side and the network side are powered by electronic power, which results in the inability to provide a stable fundamental frequency fault current, while the internal control characteristics of the converter will determine its short-circuit characteristics after the fault. At this time, the wind power converter only provides a positive sequence current, while the fault current generally does not exceed the current withstand limit of the power electronic converter with limited amplitude, thus showing the characteristics of the current source. The short-circuit current provided by the flexible converter contains both positive and negative sequence components, and the short-circuit current provided by the wind power converter is included in the short-circuit current of the flexible converter. Therefore, in order to prevent the short-circuit current amplitude from exceeding the withstand capability of the power electronics, the flexible converter must have fast blocking capability, so the flexible converter shows the characteristics of a voltage source after a fault.

Summary

In summary, the transient characteristics of the wind farm transmission line based on the analysis of two wind turbines are the basis for the study of the protection of transient

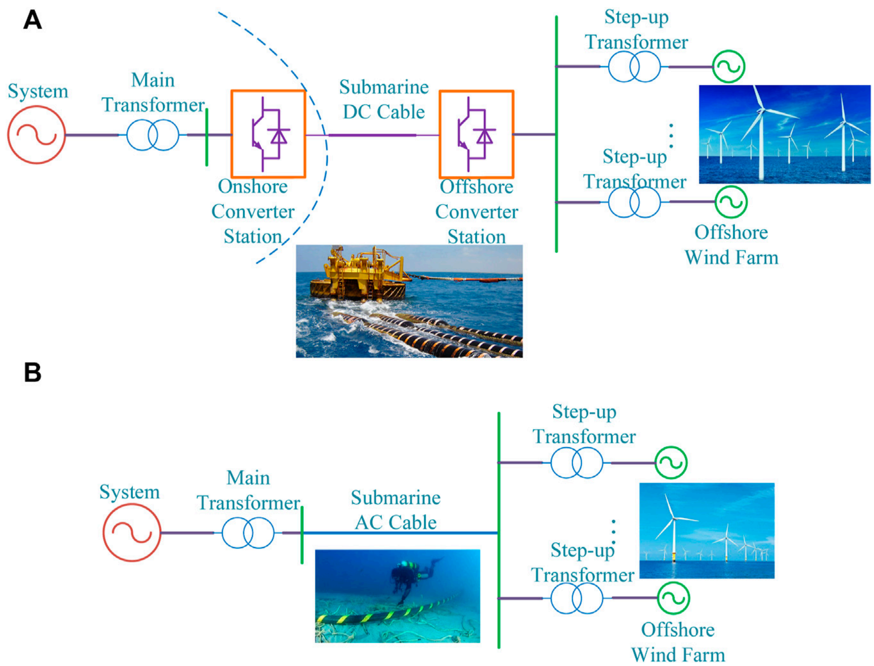

FIGURE 1 | Offshore wind farms with voltage source converter type (VSC-HVDC) and high voltage alternating current (HVAC) transmission methods.

quantities after the wind power is connected to the grid. The wind power system contains a large number of power electronics, upon which the control strategy in the converter and the topology of the system as well as the grid connection capacity will affect the transient characteristics after the fault. Moreover, the access to the wind farm makes the electromagnetic transient process of the power system more complex, and there will be harmonic oscillation. According to the traditional power grid with only a synchronous generator, many problems will be faced when analyzing the electromagnetic transient and dividing the fault process.

CURRENT STATUS OF RESEARCH ON TRANSIENT VOLUME PROTECTION FOR OFFSHORE WIND FARM TRANSMISSION LINES

Offshore wind farm transmission methods mainly include high-voltage AC transmission (HVAC) methods and high-voltage DC transmission (conventional line-commuted converter (LCC-HVDC) and voltage source converter (VSC-HVDC)) methods (Lin and Chao, 2010; Li et al., 2018b; Chang et al., 2018), which are shown in **Figure 1**. Most types of equipment such as booster stations of offshore wind farms are unattended. At this time, the relay protection equipped with electrical equipment should quickly and reliably remove the fault so as to prevent it from expanding the fault range and causing a more serious impact.

AC Transmission and Grid Feed

All offshore wind farms in the UK currently use AC convergence and AC transmission to the grid, including the London Array, the largest offshore wind farm at 630 MW, and the Hornsea Project One (i.e., the world's largest offshore wind farm under construction, which is fed via three AC 220 kV submarine cables with a length of 142 km). The first real offshore wind farm in China is the Dongtai offshore wind farm in Jiangsu with a capacity of 200 MW, which sends electricity from the offshore booster station to the central control center on the road via a 220 kV AC submarine cable. As can be seen, the AC cable is the main transmission line for the currently built offshore wind farms.

At present, most of the research on the protection of offshore wind power AC cables based on transient quantities is aimed at the protection of AC cables in collector systems, such as literature (Li et al., 2020) uses the singular value decomposition method for the protection of AC lines, which can quickly identify in-zone and out-zone faults, and the identification time is less than 5 ms. This method has implications for the protection of AC cable transmission lines, upon which there is also the use of the injection method to quickly obtain fault current for fault detection (Zheng et al., 2020). The protection of AC cable transmission lines for offshore wind power is less researched, which can be based on some of the research in offshore wind power AC cable location methods. For example, the submarine observation network fault location method based on the time difference of multi-terminal faults was proposed in a related study (Zheng et al., 2020), which uses the intelligent branch unit (BU) to determine the fault line by comparing the time difference matrix between the arrival of the wave heads before and after the fault. What is more, the method is simple to implement and accurate to locate, which provides a guarantee for the safe and reliable operation of the power system of the submarine observation network. In order to adapt to the grid connection of large-capacity offshore wind farms, compensation is often carried out by means of unified power flow controllers (UPFCs). The performance of traditional distance protection schemes is greatly affected by the nonlinear fluctuations of their output power in response to unpredictable wind speeds and the various operating modes of UPFCs, where the electrical quantities used are the transient currents of the three phases (Jia et al., 2019).

DC Transmission Grid Connection and Transmission

For offshore wind farms connected to the grid through DC transmission, the market share is 30%. Most of the offshore wind farms built in Germany use flexible DC transmission to connect to the grid. The real offshore wind power project in China is the Rudong offshore wind power flexible direct project under construction in 2021. When the offshore wind farm is sent through the flexible straight line, the fault characteristics of its converter show the characteristics of a controlled voltage source, and the rapid blocking of the DC converter will cause the fault current amplitude to be limited and the fundamental frequency characteristics to be short-lived, affecting the correct determination of the fault line by relay protection.

Considering the large distributed capacitance of cable lines in offshore wind power systems, the literature (Adetokun and Muriithi, 2021) uses a distribution parameter model with forward and reverse traveling wave amplitude ratios to determine the fault direction according to the transmission characteristics of traveling waves. The method is not only unaffected by the transient distributed capacitance current but is also applicable to offshore wind power transmission lines. For fault detection in offshore wind power access multi-terminal DC systems, a fault detection method based on transient current averaging is proposed in the literature (Cao et al., 2020), in which the transient equivalent model of the radiating multi-terminal DC system is improved, the fault analysis circuit for calculating the short-circuit current at the beginning of the fault is simplified, and the model has a high accuracy, based on which a protection scheme is implemented using transient averaging. The method requires a low sampling rate. This method requires a low sampling rate and is suitable for real-time calculations as only two addition, subtraction, multiplication, and division operations are required for each sampling point collected. When a fault occurs in an actual wind farm transmission through a DC line, the system generally requires fast action within a few milliseconds for reliable fault ride through but maybe disturbed by lightning strikes and other factors, so its reliability is yet to be verified.

Summary

For the offshore wind farm transmission line, whether it is an AC cable or DC cable transmission method, there is less research on the relevant transient quantity protection. With the development of new energy grid connection technology, the relevant grid connection technology for onshore wind power has been improved, while the grid connection technology for offshore wind power is still immature. For offshore wind power, wind farms are more affected by the environment than onshore, and the installed capacity is larger, and the volatility of the short-circuit current after a fault is also larger. As can be seen, for offshore wind power grid connection, modeling analysis is needed for the actual operating mode of the offshore and the characteristics of its turbines, etc.

CONCLUSION

This article summarizes the transient quantity protection for offshore wind farm send-out lines, including the transient characteristics of wind farms based on doubly fed wind turbines and direct-drive permanent magnet wind turbines after grid-connected faults. Based on the progress of the existing research on transient protection for wind farm feeder lines, an outlook on the protection of large-scale wind farm feeder lines is given, and suggestions for relevant research directions are given, providing a reference for the research on relay protection technology after wind power is connected to the grid.

The protection of transient quantities of wind farms connected to the grid needs further research, and future research can be carried out in the following areas:

1) With the increasing capacity of wind farms, the increasing length of the transmission lines, and the influence of factors such as the physical geography, attention needs to be paid to the non-linear, multi-timescale characteristics of the converters in power electronics and the threat to the stable operation of the system and to the protection of the line transients from lightning disturbances caused by the wideband oscillation problems they cause when disturbed.
2) Furthermore, improving the control technology research of flexible DC or multi-terminal flexible DC transmission. The input of flexible transmission devices is the medium to achieve long-distance transmission and reliable and flexible control technology is to achieve the premise of the line protection; control response under the fault current characteristics and control strategy are closely related. Explore the short-circuit current transient characteristics of wind turbine converter control strategy and DC control technology under the influence of each other, use the transient information in the whole process of fault, and then develop new principles to meet the rapid protection of the line.
3) To investigate the full process of converter control and regulation after a fault and to ensure that the control is achieved based on the principles of simplification and step-down, considering the dynamic factors in the wind turbine that have a significant impact on the electromagnetic transients. The establishment of a more accurate transient model will be a difficult task in future studies of transient protection, so it is particularly important to build a more detailed and realistic simulation model to illustrate the reliability of the protection scheme used.

4) Wind farms can be studied by retrofitting integrated protection criteria based on transient quantity protection devices and improving existing protection. Wide-area measurement technology, multi-agent technology, and intelligent algorithms can be used as applications in the field of complex grid protection. Additional pilot studies are needed to put the developed protection prototypes into field trial operation when conditions are right. In addition, issues related to wind power feeder lines with shunt reactors and the impact of reactive power compensation devices with different performance on the recovery voltage and potential supply current of the faulty phase need to be considered in order to study fault identification schemes applicable to wind power feeder lines (Wang et al., 2018).

AUTHOR CONTRIBUTIONS

XS: conceptualization, writing—reviewing, and editing; XY: writing—original draft preparation and investigation; JC: supervision; and XJ: visualization and contributed to the discussion of the topic.

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