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OPINION
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Research Progress and Challenges of Transient Protection for Transmission Lines in Large-Scale Wind Farms

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INTRODUCTION

With the continuous advancement of renewable energy grid-connected technology, wind power plays an important role in it due to its mature technology and is developing rapidly around the world (Rezaei et al., 2020; Tian et al., 2017). The safe operation of the systems will be affected by randomness, intermittency, and volatility after large-scale wind farms are connected to the grid, among which impact on relay protection is the most significant (Telukunta et al., 2017; Xi et al., 2016). There are many differences in fault characteristics after large-scale wind farms are connected to the grid compared with traditional power grids (Yang et al., 2016). These differences are mainly reflected in frequency offset, weak feed, and high harmonics, which cause problems such as incorrect operation and decreased sensitivity when traditional power frequency protection is used in large-scale wind farms (Niknezhad and Sadesh, 2021; Ma et al., 2020). A large-scale wind farms system, the current waveform on the wind farm after a three-phase short-circuit, and the protection coordination scheme of the transmission line are shown in **Figure 1**.

With the continuous rise of global energy consumption and changes in load demand (Yang et al., 2020a; Sun and Yang, 2020), the performance of relay protection is required to develop towards higher-speed operation due to the nonlinearity and fragility of electronic power equipment (Yang et al., 2020b). After a fault, rich fault information is available in high-frequency transients, and the time window required for transient protection is short (Chen et al., 2019). The rapidity of transient protection action is more in line with the requirements of modern power systems. Therefore, the study of transient protection is a current developmental trend in relay protection. The idea of relay protection based on transient is that the transmission line is protected at high speed through fault transient information. In recent years, research based on the principle of transient protection mainly includes time-domain distance protection, protection based on double-ended waveform comparison, and protection based on fault traveling waves. In this paper, the current transient protection methods for large-scale wind farms are summarized. The advantages and disadvantages of each type of method are discussed. The latest progress and challenges of transient protection for large-scale wind farms are summarized.

Fault Transient Characteristics in Large-Scale Wind Farms

Intermittency and randomness of wind power have an impact on fault characteristics and analysis of transient characteristics after a fault is a basis for studying the transient protection of wind power systems. At present, in the research of relay protection of wind farms, wind farms with equivalent characteristics of a wind turbine are often used instead of detailed modeling of wind turbines, which is to reduce the complexity of fault characteristic analysis. There are many hardware devices such as crowbars in wind farms, which are used for low-voltage ride-through of wind turbines and will make transient waveform after a fault more complicated (Chang et al., 2018). Relevant studies have shown

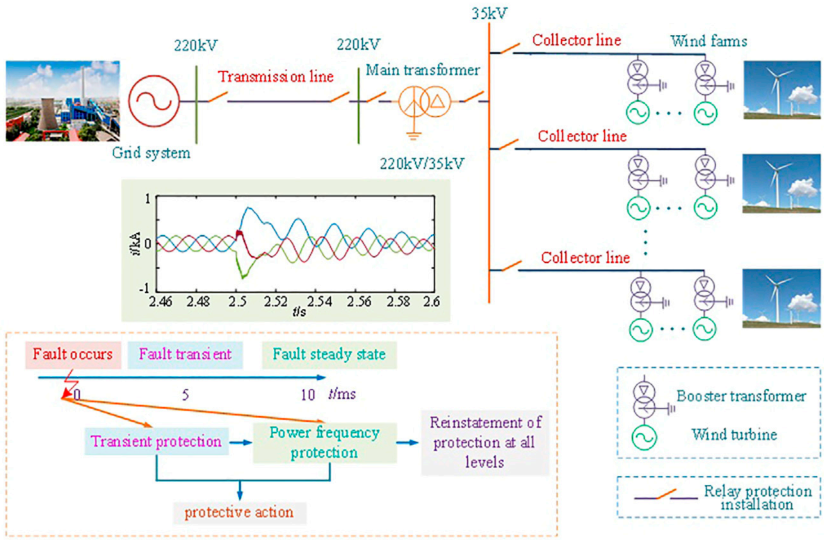

FIGURE 1 | Large-scale wind farms system, short-circuit current waveform, and protection coordination scheme of the transmission line.

that when a fault occurs, short-circuit current increases. At this time, under the control of wind turbines, increased short-circuit current is suppressed. The waveform is controlled and contains harmonics. Fault current waveform is an attenuated non-power frequency sine wave and a non-power frequency sine wave with volatility (Ma et al., 2018). It can be seen from **Figure 1** that the control strategy of converter devices for wind turbines has an impact on the short-circuit current characteristics (Yin, 2021).

Wind power system contains a large amount of electronic power equipment and transient characteristics after a fault will be affected by control strategy in the converter, topology of the system, and grid-connected capacity. Grid connection of large-scale wind farms makes the transient process more complicated and there will be problems such as harmonic oscillation. However, if a transient component is analyzed based on the traditional power grid that only contains synchronous generators, there will be many problems in identifying faults (Liu S. et al., 2021). The time window required for transient protection is short, and generally only sampling data within a few milliseconds is required. It is less affected by the control of the converters in wind farms. Therefore, it is necessary to study protection suitable for large-scale wind farms.

Time-Domain Distance Protection Based on Transients

Time-domain distance protection is an algorithm in which transient voltages and transient currents are used to solve differential equations.

Zhang et al. (2017) changed distance protection based on FFT to protection based on the RL model by transient component and a notch filter is applied to the algorithm. Saber (2020) proposed a new method based on one-end current measurements. Fan et al. (2020) proposed a time-domain distance protection that is not affected by transition resistances. Zhang et al. (2021) used waveform correlation analysis in time-domain distance protection.

The protection does not involve frequency domain information and will not be affected by the frequency offset of wind farms. It is not affected by how the system operates. However, when a centralized parameter is used as the model, the influence of distributed capacitance on the transmission line is not considered. When the transmission line is long, the influence of distributed capacitance is greater, which may affect the algorithm. It is also influenced by high-frequency components. The problem of inaccurate calculation may occur for near-end fault.

Transient Protection Based on Double-Ended Waveform Comparison

Protection based on the comparison of double-ended waveforms refers to the difference in the waveforms of transient current and voltage at both ends of transmission line under internal faults and external faults. According to characteristics of grid-connected renewable energy, when an external fault occurs, there is a penetrating current in the transmission line, and the difference in short-circuit current waveform on both sides is very small. However, when an internal fault occurs, short-circuit current on wind farm presents non-power frequency characteristics. Short-circuit current waveform on the grid is a sinusoidal waveform dominated by power frequency. The protection judgment is formed according to the above differences.

Chen et al. (2018) proposed an improved Hausdorff distance algorithm for fast identification of a fault. Lv et al. (2019) adopted the differential current within 5 ms after a fault and used the least-squares curve fitting to extract the main frequency of the transient current waveform. The fault phase is judged according to this criterion. Zheng et al. (2020) proposed a new protection scheme by correlation analysis of fault current component based on a multi-agent system. Zhao et al. (2020) used a clustering algorithm to characterize class attributes of historical samples for fault current under different operating conditions. The distance similarity criterion is used to determine a fault. Yang Q. et al. (2020) proposed a new protection method based on the time-domain waveform, which is applied to large-scale wind farms. Jia et al. (2021) used Spearman's rank correlation coefficient to identify faults. Zheng et al. (2022) proposed new protection based on cosine similarity. The protection device has been installed and put into operation in the wind farm in Inner Mongolia, China.

The protection principle is clear and a higher sampling rate is not required. It is suitable for a weak output of renewable energy. However, errors of double-ended data synchronization, errors of current transformer transmission, and influence of time window length need to be considered.

Transient Protection Based on Fault Traveling Wave

Transient protection based on fault traveling wave refers to protection in which polarity, amplitude, and other information of initial fault traveling wave are utilized. Generally, polarity and amplitude of double-ended current traveling waves are used to construct the protection criterion.

Mahfouz and El-Sayed. (2020) proposed a one-ended protection method based on cross-alienation methodology, which can be applied to the protection of offshore wind power HVDC transmission cables. Biswas and Nayak. (2021) used magnitude change of positive-sequence current traveling wave for fault detection. Liu Y. et al. (2021) proposed a protection method suitable for offshore wind power, whose traveling wave direction protection at both ends of the transmission line is used to determine fault direction. Khalili et al. (2021) used game theory to identify fault traveling waves, which can be used for mixed transmission forms of overhead lines and cables.

The protection is suitable for transmission lines that are greatly affected by distributed capacitance currents and are not affected by current transformer saturation. However, sampling frequency above 100 kHz in traveling wave protection, so higher sampling frequencies are required. It is affected by electromagnetic transient signals such as lightning waves and operating waves. It is also susceptible to harmonic interference. The problem of inaccurate calculation may occur for near-end fault.

CONCLUSION

1) For time-domain distance protection, transient voltage and transient current are used to solve differential equations, which do not involve frequency domain information of signal and are not affected by the operating mode of the system. However, there may be a dead zone for near-end fault. It is affected by distributed capacitance of a long transmission line.
2) Transient protection based on double-ended waveform comparison is less affected by transition resistance and noise. It does not require a high sampling frequency and is suitable for wind farms with weak output. However, there may be errors in the synchronization of double-ended data and it is affected by transmission errors of the current transformer.
3) Transient protection based on fault traveling wave is not affected by transient distributed capacitance current and is less affected by the transition resistances. However, if the sampling frequency is high, there will be a problem with threshold setting. There may be a dead zone for near-end fault.

Challenges of transient protection for wind farms in the future also include: with the construction of AC and DC hybrid systems, it is necessary to explore time limit and threshold coordination of low voltage ride through, high voltage ride through, and low and high voltage cascading faults and transient protection for large-scale wind farms. Converter control adjustment acts on the whole process after a fault. On the basis of ensuring the realization of control, according to principles of simplification and order reduction, dynamic factors that have an important impact on transient wind turbines are fully considered. In addition, the design requirements of wind turbines for onshore and offshore wind farms are very different, mainly affected by the environment and technology. Transient characteristics These differences will be affected by these differences. Therefore, it is necessary to carry out corresponding transient protection research for different wind power systems.

AUTHOR CONTRIBUTIONS

HS contributed to the funding. XJ contributed to writing the draft. YT and ZB contributed to the investigation and resources, respectively.

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