Transient Voltage Stability Analysis of Offshore Wind Power Systems

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ABSTRACT

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| With the development of science and technology, the cost of offshore wind power development and transmission has gradually decreased, making offshore wind power technology a research hotspot. The installed capacity has been increasing year by year. China has abundant offshore wind energy resources, which are much richer than those on land and are available for exploitation. Offshore wind speeds are stable and do not produce harmful substances. Therefore, studying the transient voltage stability of offshore wind power grid-connected systems to improve the utilization efficiency of offshore wind power and protect the ecological environment is critical. After large-scale wind power is connected to the grid, ensuring the stability of the system's transient voltage becomes crucial. This paper aims to deeply study the transient voltage stability of offshore wind farm grid-connected systems, providing theoretical support for the subsequent design and operation of offshore wind farms. A simulation model of a typical power system integrated with offshore wind farms was established using PSAT. Relevant transient voltage stability indices were calculated, and the impact of varying wind speeds on the transient voltage stability of the grid-connected system was investigated. Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) were installed for comparative analysis. The results demonstrate that excessively low wind speeds degrade the system's transient stability, and the installation of SVC provides superior improvement in transient voltage stability compared to STATCOM. |

*Keywords: Offshore wind farm, Transient voltage stability,* *Grid-connected system,* *Reactive power compensation device*

1. INTRODUCTION

With the increasing global attention on environmental issues and the expansion of human activities into the oceans, the development of marine energy has become one of the important ways to alleviate the energy crisis and protect the environment. China's offshore wind energy market is vast, being one of the largest wind power markets globally, and also the offshore wind energy market with the greatest potential for future development. China is rich in offshore wind resources, and offshore wind power will inevitably become a major choice for vigorously developing new energy sources, playing a pivotal role in the transformation of the energy structure. In the future, it will, along with the "West-to-East Power Transmission" and local power sources, play a crucial role in supplying power to the load centers in the eastern regions. Currently, offshore wind power has become a research hotspot and a key focus in both academic and industrial circles [1]. Therefore, it is crucial to conduct a comprehensive reliability assessment of the entire system during the planning phase of offshore wind farms.

This paper uses PSAT (Power System Analysis Toolbox) to establish a simulation model of an offshore wind farm (using PMSG technology) connected to a typical power system. Under fault conditions, relevant common transient voltage stability indicators, such as the critical clearing time for short-circuit faults, are obtained to verify the correctness of these indicators. By setting up short-circuit and line-break faults, the transient voltage stability of the system is examined, and relevant indicators are calculated. Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) are installed respectively, and simulation experiments are conducted to compare which solution can better improve the transient voltage stability of the grid-connected system.

1) Use PSAT to establish a simulation model of an offshore wind farm connected to a typical power system, and obtain relevant common transient voltage stability indicators, such as the critical clearing time for short-circuit faults.

2) Assess the transient voltage stability of the system, including short-circuit and line-break faults, and calculate relevant parameters.

3) Install two different compensators, SVC and STATCOM, to evaluate their impact on the transient voltage stability of the grid-connected system.

2. Research on Transient Voltage Stability of Grid-Connected Offshore Wind Farm Systems

In recent years, the scale of grid-connected offshore wind farm systems has developed rapidly, accompanied by the emergence of various types of wind turbines. Among them, the most mainstream are two categories: the Doubly Fed Induction Generator (DFIG) and the Permanent Magnet Synchronous Generator (PMSG). More importantly, the impact of grid-connected systems on voltage stability cannot be overlooked. Voltage flicker and fluctuation are common negative effects, the severity of which can even lead to the collapse of the power system voltage.

In the early days, ordinary asynchronous wind turbines became mainstream due to their simple structure, reliable operation, and economical price. However, their wind energy utilization efficiency was low, and their power control performance was subpar, requiring continuous absorption of reactive power from the grid when connected. In recent years, with the rapid development of grid-connected offshore wind farm systems, to enhance the power generation efficiency and reliability of wind power systems, ordinary asynchronous wind turbines have gradually been replaced by DFIG and PMSG, which are more suitable for wind power generation [2].

**2.1 DFIG Grid-Connected System**

The components of a DFIG grid-connected system include the wind turbine, gearbox, generator, and dual PWM converter. The doubly-fed wind turbine utilizes virtual synchronous machine technology to simulate the motion equations of a synchronous machine, possessing output characteristics such as inertia and damping, thereby enhancing the transient synchronization stability of the grid-connected system [3]. As a wind energy collector, the wind turbine transfers its energy to the low-speed shaft of the gearbox, which is responsible for increasing the shaft's operating speed to drive the generator for power generation. The electricity generated by the generator is directly delivered to the grid through the stator windings, and the electricity produced by the generator is transmitted to the grid through the rotor windings and the dual PWM converter.

**2.2** **PMSG Grid-Connected System**

PMSG Grid-Connected System consists of a main circuit and a control circuit, presenting a symmetrical structure centered around the capacitor. The generator and the machine-side converter form the left side, while the grid-side inverter and the main grid constitute the right side. The wind rotor collects wind energy through the rotation of its blades, which is then rectified and processed by the motor. When the external airflow reaches the set value, the wind turbine unlocks and begins to operate. The wind energy is transferred from the wind rotor to the gearbox to increase the rotational speed, driving the generator to produce electricity. The output alternating current is rectified by the dual PWM converter and then fed into the grid, effectively improving output efficiency and reducing harmonics [4].

Currently, doubly-fed induction wind turbines and direct-drive permanent magnet wind turbines are the mainstream types. Doubly-fed generators have lower costs but slightly lower efficiency, making them suitable for large wind farms. Direct-drive permanent magnet generators require less maintenance and offer high reliability, but they face issues such as large size, high bearing requirements, and susceptibility to demagnetization. In offshore environments, they require further improvements in anti-corrosion and maintenance methods. Additionally, doubly-fed generators adjust the power factor through a speed regulator, while direct-drive permanent magnet generators can directly output wind energy.

The reasons for the dominance of doubly-fed generators include the large size of direct-drive units, high bearing requirements, insufficient anti-corrosion properties, and maintenance difficulties. However, with the development of power electronics technology, the reduction in inverter costs, and the increasing demand for reliability, the disadvantages of doubly-fed generators are gradually becoming apparent. In the future, direct-drive permanent magnet wind turbines are expected to replace doubly-fed generators, especially in offshore wind power and low-speed applications, where technologies like permanent magnet motors will hold greater advantages.

**2.3 *L* Index and *L-P* Sensitivity Index**

Taking the IEEE 39-bus system as an example, the impact of increased active power output from wind farms on the grid-connected node voltage and the *L* index was studied, revealing the influence of wind power integration on transient voltage stability. The *L* index can be used to identify weak points in the system; the higher the *L* value, the greater the vulnerability of the node, especially for load nodes far from generator nodes, which are more likely to become weak points. The *L*-*P* sensitivity intuitively reflects the impact of changes in wind power output on the *L* value of grid-connected nodes, helping to enhance the understanding of wind power integration characteristics. When the active and reactive power output of the wind farm remains unchanged, an increase in line reactance leads to a decrease in the voltage of the grid-connected bus, weakening transient voltage stability. Improving line resistance can enhance voltage levels, increase the stability margin, and improve the accommodation capacity of the wind power system. Switching from constant power factor control to constant voltage control can significantly improve voltage stability, reduce the *L* index value, and optimize the network topology. After increasing the wind power integration capacity, the voltage and its stability tend to stabilize, but sufficient reactive power support is required to ensure system stability and avoid transient stability issues [5,6].

3. Research on Common Transient Voltage Stability Indicators

**3.1 Factors Influencing Transient Voltage Stability**

With the in-depth study of voltage stability, the process of voltage collapse itself has become a widely recognized dynamic phenomenon in the field of voltage stability research [7]. The root causes of voltage instability lie in insufficient reactive power and limited network transmission capacity. During the development of voltage collapse incidents, discrete control behaviors and load characteristics play an indispensable role. Therefore, when considering the practical application of power systems, it is essential to comprehensively consider various factors that may lead to transient voltage instability [8,9]. When low voltage worsens reactive power balance, creating a positive feedback loop that leads to voltage decline, dynamic loads need to automatically adjust their intrinsic admittance characteristics to achieve input/output active power balance. However, such adjustments may result in voltage instability, triggering various dynamic behaviors. Induction motors are the primary loads that impact transient voltage stability, referred to as load characteristics; generator units and their control components constitute the core part of the entire system. At this point, if the generator can maintain its active power output unchanged at lower rotor speeds, it can avoid entering weak excitation circuits and enhance grid stability, known as generator characteristics.

**3.2 Transient Voltage Stability Criterion**

The critical clearing time (*t*CCT) for short-circuit faults is a core indicator for evaluating transient stability, reflecting the system's ability to recover after being disturbed. In the stability assessment of power systems, evaluating transient voltage instability based on the acceptable level of transient voltage is a practical criterion [9]. To comprehensively consider the withstand capability of transient voltage, it is necessary to thoroughly assess the minimum transient voltage and the duration of transient voltage dips. The reliability criteria for the operation of the Western Interconnected Power System in the United States stipulate the following requirements for acceptable transient voltage dips: for N-1 component faults, the time during which the transient voltage remains below 80% of the rated voltage should not exceed 400 ms; for N-2 component faults, the time during which the transient voltage remains below 80% of the rated voltage should not exceed 800 ms. Due to the current shortcomings in the configuration of power system dispatching automation equipment and communication technology in China, this indicator cannot fully meet the needs of the development of China's power system. Generally, the voltage at key 220 kV and above busbars should be able to recover to a level not lower than 75%. When the load bus voltage recovers to the specified voltage limit or above, it can be concluded that the system can maintain transient voltage stability, thereby avoiding the occurrence of transient voltage instability [10].

**3.3 Analysis of Transient Voltage Stability Indicators**

As the critical clearing time (*t*CCT) increases, the duration of transient disturbances that the grid connected to the wind farm can withstand also extends. With the continuous penetration of wind power generation, its impact on the transient stability of the power system becomes increasingly significant. As *t*CCT shortens, the transient stability margin of the system gradually decreases. When the fault duration exceeds *t*CCT, the system voltage will continue to oscillate until it eventually collapses. During asymmetric operating conditions between wind turbines and the power system, precise analysis is challenging due to the significant harmonic components in the generator rotor excitation current. For the assessment of transient voltage stability, the calculation of *t*CCT is a crucial core indicator under various disturbance scenarios. As *t*CCT increases, the transient voltage stability of the system shows a gradual strengthening trend.

For a specific operating mode and disturbance sequence of the system, the bisection method and trial method are typically used to search for the *t*CCT under that disturbance sequence.

Before applying the bisection method, it is necessary to determine the maximum critical clearing time (*t*max) and convergence accuracy *ϵ* (such as *ϵ* = 0.001) to ensure the accuracy of the search results. The specific steps are as follows: In the first step, set the fault clearing time to *t*max /2 and perform a time-domain simulation. If the system remains stable, wait for 3tcctmax/4 in the second step; otherwise, proceed with the subsequent steps using *t*max /4 until the *t*CCT value meets the required precision standard.

Alternatively, the trial method can be used to determine *t*CCT. First, predict and select a fault clearing time for a time-domain simulation, and observe whether the load bus voltage can recover to a stable state, i.e., whether it can restore to 75% or above. If it cannot recover, the fault clearing time should be appropriately reduced; conversely, if it can recover, the clearing time should be appropriately increased. Repeat this simulation step until the critical time is found where the load bus voltage just barely recovers to a stable state.

4 Simulation Analysis of Transient Voltage Stability in Grid-Connected Offshore Wind Farm Systems

**4.1 Establishment of a Simulation Model for Grid-Connected Offshore Wind Farm Systems**

The simulation and analysis of the interaction between offshore wind farms and the surrounding power system aim to assess the reliability, stability, and economic efficiency of the grid, providing decision-making support for the design and operation of wind farm integration into the power system. Using PSAT simulation software, we constructed a simulation model to simulate an offshore wind farm (including Phase I and Phase II projects) connected to a system with three machines and nine nodes on a single 230 kV transmission line. Based on this, the model was simplified according to actual conditions, taking into account changes in wind turbine output characteristics. The constructed model covers various aspects such as wind speed, wind turbine generators, transformers, and reactive power compensation equipment. By performing equivalent modeling of the entire system, a complete three-phase mathematical model was obtained. Using the established power system model, different fault types were simulated to determine the maximum clearing time for system short-circuit faults and to collect a corresponding number of sample data. Based on these sample data, the steady-state power flow distribution curve of the system was derived. To compare the transient voltage stability of the grid-connected system under different wind speeds, we set varying wind speeds. Based on the results obtained, the optimal solution was selected to improve the system design, making it more reliable and stable in performance. For the transient voltage stability of the grid-connected system, we compared the impacts of STATCOM and SVC devices and proposed improvement measures to enhance its stability.

**4.1.1 Wind Speed Model and Wind Turbine Model**

As shown in Figure 1, the model established in this paper encompasses both wind speed and wind turbine models. The model presented here includes wind forces, as well as a variable-speed wind turbine generator and a direct-drive permanent magnet synchronous generator.



**Fig. 1. Wind Speed and Wind Turbine Model**

Due to the random, fluctuating, and intermittent nature of wind fields, wind fields are typically simulated using random wind to calculate wind speed. At a specific relative height, the variation in wind speed exhibits randomness, which is referred to as random wind and is commonly described using parameters such as random noise wind speed. The Weibull distribution, as a probability density function, has been successfully applied to describe wind speed distribution patterns and is widely recognized as a probability model that closely aligns with actual wind speed distributions [11].

**4.1.2 Offshore Wind Farm 3-Machine 9-Node System**

As shown in Figure 2 below, it is the model of an offshore wind farm connected to a 3-machine 9-node system[12].

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**Fig. 2. Offshore Wind Farm Connected to a 3-Machine 9-Node System Model**

1) Wind Speed Model and Wind Turbine Model. During the construction of this offshore wind farm model, actual engineering data from a real intertidal offshore wind farm project were referenced and optimized. The intertidal zone refers to the coastal area that extends from the daily low tide point to the daily high tide point, forming a vast region influenced by tidal movements. Offshore wind turbines selected for this model are direct-drive permanent magnet synchronous generators, set as *PQ* generation-type nodes. The generator outlet bus is connected to the *PQ* generation-type node and the wind turbine units. In the first phase of the wind farm, a total of 33 WTG121-3000 units are installed, each with a rated capacity of 3 MW, a rated voltage of 0.69 kV, and a total capacity of 99 MW. The second phase of the wind farm has an installed capacity of 78 MW, consisting of 26 WTG121-3000 units, each with a rated capacity of 3 MW and a rated voltage of 0.69 kV. The WTG121-3000 model has a cut-in wind speed of 3 m/s and a cut-out wind speed of 22 m/s, with a rated wind speed of 11 m/s.

2) Transformers. To improve the efficiency of the wind farm's power transmission and transformation system, the voltage is boosted in two stages. The generator outlet voltage is increased from 0.69 kV to 35 kV, and the main substation voltage is further increased from 35 kV to 220 kV. The short-circuit voltage ratio of the primary step-up box transformer is 6.25%, while that of the secondary step-up main transformer is 18%.

In the first phase of the project, a main transformer with a capacity of 100 MVA was installed, and in the second phase, a main transformer with a capacity of 80 MVA was installed. When one main transformer or the corresponding high/low voltage distribution equipment is under fault or maintenance, the other main transformer can still transmit most of the power generated by the wind farm through the shared substation in the second phase, thereby reducing wind curtailment.

3) Transmission Lines. The impedance of the 35 kV AC submarine cable collection line within the wind farm is 0.28 + j0.132 Ω/km, with a length of 5 km. The impedance of the 220 kV AC overhead line connecting the wind farm to the grid is 0.039 + j0.308 Ω/km, with a length of 20 km.

4) Reactive Power Compensation Devices. Both the first and second phases are equipped with a set of 35 kV dynamic reactive power compensation devices, each with a rated capacity of 50 MW. Since shunt capacitor banks are used for compensation, a large inrush current may occur in the system during grid faults. Using the built-in STATCOM and SVC models in PSAT simulation software, we will evaluate the impact of different devices on the transient voltage stability of the grid-connected system.

5) System Frequency. The system operates at a frequency of 50 Hz. The original 3-machine 9-node system (a built-in model in PSAT software) had a frequency of 60 Hz, which has been modified to 50 Hz as required.

**4.3 Simulation Study of the System under Short-Circuit and Open-Circuit Conditions**

**4.3.1 Simulation Study of the System under Short-Circuit Conditions**

A short-circuit fault is set at the beginning of the transmission line of the wind power system, as shown in Figure 3. When the system experiences a large disturbance such as a short-circuit fault, the relay protection acts to clear the fault. The critical fault clearing time is an important indicator for assessing the transient voltage stability of the grid-connected system.

In this experiment, a trial method is used. Under the condition of the rated wind speed of 15 m/s, the critical fault clearing time obtained by the trial method is 0.32 s. The fault start time is set to 5 s, and the fault end time is set to 5.32 s. Equation (1) provides the calculation method for the critical fault clearing time.

 (1)

Where is the critical fault clearing time,  is the fault end time, and  is the fault start time.

The practical criterion for achieving transient stability in this system is that the voltage at the central bus can recover to 75% or above. The conclusion can be drawn by examining the power flow calculation results and the time-domain simulation images of the system model. As shown in Figure 3, the voltage image of the Bus16 grid connection point in the time-domain simulation is presented. The per-unit voltage value of the Bus16 grid connection point in the power flow calculation is 0.88974, and the node voltages have all recovered to above 75%. Therefore, the grid-connected system has achieved transient voltage stability.



**Fig. 3. Transient Voltage Stability Curve of the System under Short-Circuit Fault Condition**

If the fault clearing time exceeds the critical fault clearing time, the grid-connected system will experience transient voltage instability. Now, taking 5.40 s as the fault clearing time, the power flow calculation and time-domain simulation of the system model are performed. As shown in Figure 4, the voltage image of the Bus16 grid connection point in the time-domain simulation is presented. The per-unit voltage value of the Bus16 grid connection point is 0.00199, which has not recovered to above 75%. Therefore, the grid-connected system has not achieved transient voltage stability and has experienced transient voltage instability.



**Fig. 4. Transient Voltage Instability Curve of the System Node under Short-Circuit Fault Condition**

**4.3.2 Simulation Study of the System under Open-Circuit Conditions**

A line disconnection fault was set at the initial segment of the transmission circuit in the wind power system, followed by power flow calculation and time-domain simulation experiments of the grid-connected system.

The reclosing function of the circuit breaker was utilized, configured to open at 5 seconds and close at 6 seconds. Through power flow calculation and time-domain simulation, the PSAT system prematurely terminated the computation, leading to the conclusion that the circuit breaker caused structural instability in the system under the line disconnection state, resulting in transient voltage instability.

**4.4 Study on the Impact of Wind Speed on System Transient Voltage Stability**

Due to the stochastic nature of wind speed, its influence on the transient voltage stability of offshore wind farm grid-connected systems varies significantly under different wind conditions. The cut-in wind speed for the system in this study is 3 m/s, and the cut-out wind speed is 22 m/s. Therefore, this paper conducts multiple simulation experiments under system short-circuit conditions at different wind speeds to determine the critical clearing times for various fault states, aiming to investigate the impact of wind speed on the transient voltage stability of the system. The specific results are presented in Table 1.

**Table 1. Comparison of Wind Speeds and Corresponding Critical Fault Clearing Times**

|  |  |
| --- | --- |
| **Wind Speed (s)** | **Critical Fault Clearing Time (s)** |
| 3  4 | 0  0 |
| 5 | 0 |
| 6 | 0 |
| 7 | 0 |
| 8 | 0.06 |
| 9 | 0.32 |
| 10 | 0.32 |
| 11 | 0.31 |
| 12 | 0.33 |
| 13 | 0.32 |
| 14 | 0.33 |
| 15 | 0.32 |
| 16 | 0.32 |
| 17 | 0.30 |
| 18 | 0.32 |
| 19 | 0.32 |
| 20 | 0.33 |
| 21 | 0.32 |

As shown in the table, a significant turning point occurs at a wind speed of 8 m/s, where the critical fault clearing time decreases substantially, indicating a notable reduction in the system's transient voltage stability. For wind speeds between 3 m/s and 7 m/s, the critical fault clearing time approaches 0 due to the rounding of the operational fault clearing time to two decimal places.

**4.5 Improving Transient Voltage Stability of Grid-Connected Systems**

To enhance the transient stability of the system, three measures can be adopted. The first is to strengthen the electrical structure compactness by reducing the electrical distance. The second is to narrow the power or energy gap between mechanical and electromagnetic systems, as well as between loads and power sources, to achieve a new equilibrium state. The third is to reduce line impedance through various methods during non-fault periods. To prevent further escalation of incidents, a series of measures must be taken, including but not limited to system islanding, to ensure system stability.

In this study, we respectively installed SVC and STATCOM at the Bus8 node. The fault condition was set to a short-circuit state to compare their impacts on the transient voltage stability of the system.

For each wind speed, multiple time-domain simulations are conducted for both models, and the critical fault clearing time is determined using probabilistic statistical methods. The specific results are presented in Table 2.

**Table 2. Comparison of Critical Fault Clearing Times for SVC and STATCOM under Different Wind Speeds**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Wind Speed (s)** | **Critical Fault Clearing Time for SVC** **(s)** | | **Critical Fault Clearing Time for STATCOM (s)** | |
| 3 | 0 | | 0 | |
| 4 | 0 | | 0 | |
| 5 | 0 | | 0 | |
| 6 | 0 | | 0 | |
| 7 | 0 | | 0 | |
| 8 | 0.09 | | 0.02 | |
| 9 | 0.37 | | 0.03 | |
| 10 | 0.37 | | 0.03 | |
| 11 | 0.37 | | 0.03 | |
| 12 | 0.37 | | 0.03 | |
| 13 | 0.37 | | 0.03 | |
| 14 | 0.37 | | 0.03 | |
| 15 | 0.39 | | 0.03 | |
| 16 | | 0.38 | | 0.03 |
| 17 | | 0.36 | | 0.03 |
| 18 | | 0.37 | | 0.02 |
| 19 | | 0.37 | | 0.03 |
| 20 | | 0.36 | | 0.02 |
| 21 | | 0.37 | | 0.03 |

From the table above, it can be observed that after installing the SVC compensator, the critical fault clearing time under short-circuit conditions is longer than that without the compensator, indicating that the SVC compensator is more beneficial for improving the system's transient voltage stability. Conversely, after installing the STATCOM compensator, the critical fault clearing time under short-circuit conditions is shorter than that without the compensator, suggesting that the STATCOM compensator is detrimental to the system's transient voltage stability.

5. Conclusion

This paper aims to explore the transient voltage stability of grid-connected systems in offshore wind farms, delve into the fundamental principles of doubly-fed induction generators and direct-drive permanent magnet generators, analyze the impact of wind speed on the transient voltage stability of the system, and propose effective measures to optimize the transient voltage stability of the grid-connected system.

Using PSAT software, a model of the grid-connected system for offshore wind farms was established. The paper elaborates on the parameters and working principles of the wind speed model, wind turbine model, and components such as transformers, leading to the following conclusions.

1) Utilizing the established model, the study investigates the critical fault clearing time under two different disturbances: system short-circuit and line disconnection, revealing the impact of different fault types on the transient voltage stability of the system.

2) Through simulation experiments of short-circuit faults at various wind speeds, the paper determines the fault limit clearing time at each wind speed. It is found that at a wind speed of 8 m/s, the *t*CCT rapidly decreases, and when the wind speed is below 7 m/s, the *t*CCT approaches 0, significantly reducing the transient voltage stability of the system. This identifies wind speeds that are detrimental to the transient voltage stability of the system.

3) By installing SVC and STATCOM at Bus8 of the system and conducting time-domain simulations of short-circuit faults at various wind speeds, the paper compares the fault limit clearing times after the installation of SVC and STATCOM, concluding that SVC is more beneficial for improving the transient voltage stability of the system.

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