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A Comparative Study on Methods of Connecting Large-Scale Offshore Wind Farms into Power Systems

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Abstract

The paper uses PSS/E software to study connecting an offshore wind farm with 864 MW into the 2015 Taiwan power system. Major simulation works include: steady-state power flow, fault current computation, transient stability analysis and the impact analysis on critical fault clearing time. Three connection methods, i.e., single-point, separate-point and multi-point connection, are proposed, in which the single-point connection is divided into two voltage levels (161kV and 345kV). During the steady-state operation, simulation results indicate that the 345 kV single-point connection method demonstrates the best performance. In addition, the fault current from a wind farm is partially determined by its connection location. In terms of transient stability, when grid faults take place, the 161kV single-point connection method appears to report the smallest voltage drop as compared to other connection scenarios. Its amplitude of frequency disturbance, however, is the greatest of all connection scenarios. As for the analysis on critical fault clearing time, simulation results indicate that the critical fault clearing time in all connection cases is approximately two times greater than that required by the Taipower standard. Simulation results in this study can be expected to provide valuable guidelines for connecting offshore wind farms into the power systems in the future.

Keywords: Offshore wind farm, connection methods, steady-state power flow, fault current computation, transient stability, critical clearing time

1. Introduction

At present, the EU member states and other countries, such as China and U.S., are planning a significant expansion of the wind power capacity, especially offshore [1]. The reason for increasing offshore wind power is that wind speed offshore is potentially higher than onshore, which leads to a much higher power production. A 10% increase in wind speed results theoretically in a 30% increase in power production. Grid connection is a critical factor for successful large scale integration of offshore wind power. In [2], a comparative study between two different grid building strategies for offshore wind farms (302 GW installed wind capacity) in the North Sea is presented. These two strategies include the strategy based on radial wind farm connections to shore and point–to–point interconnections between countries, called radial grid, and the strategy based on the use of offshore nodes to build an HVDC offshore grid, called offshore grid. The analyzed results show that the offshore grid strategy is better than the radial one. This study clearly testifies to the importance of careful planning and design in the development of large-scale offshore wind farms.

As countries around the world all strive to increase the penetration of renewable energy in power generation, power system safety, stability, and quality become a crucial issue. A large-scale wind farm brings a huge volume of power into the system so that existing lines may be overloaded, and even the capacity of equipment and facilities may fail to cope with the connection of wind farm into power system, thereby generating various problems [3]. Comprehensive study of wind farm location and connection

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methods is thus an issue of imperative importance. These connection methods can be evaluated by the system simulation analyses such as steady-state power flow, short-circuit current, and transient stability [4] after the wind farm is integrated into the system. Moreover, the safety capacity, unit dispatch strategies, and possible protection strategies of the wind farm when the system experiences grid faults are further major issues for in-depth analysis [5].

The study aims at evaluating the methods of connecting the Zhanghua Offshore Wind Farm in Taiwan (with a scheduled capacity of 864 MW) into the 2015 Taipower system. Three connection methods – single-point connection, separate-point connection, and multiple-point connection – are examined, and issues related to steady-state flow and transient stability are analyzed so as to understand the impacts of connecting the wind farm into the power system and to provide relevant insights for future development of large-scale wind farms.

2. Introduction to the Simulation System

In the study, the single-, separate-, and multiple-point connection methods, along with different transmission voltage levels (161kV and 345kV), were evaluated for a large offshore wind farm planning in Taiwan. The 161kV single-point connection method is shown in Fig.1, where the voltage is transferred from 23.9kV to 161 kV at an offshore substation and then connects into the Taiwan grid in a single point. For the separate-point connection method, the total capacity of the wind farm is equally divided into two independent parts with a capacity of 432 MW each, and they are connected to the Taiwan grid at different bus, which is shown in Fig.2. The third connection method is shown in Fig.3, where the offshore wind farm is not separated into 2 or more parts but is interconnected into the Taiwan grid at 2 different onshore buses. The circuit topology of the fourth method, as shown in Fig.4, is identical to the single-point connection method but the voltage is transferred from 23.9kV to 345 kV at an offshore substation.

In the study, the 864MW Zhanghua Offshore Wind Farm is scheduled for connection to the 2015 Taiwan power system. By 2015, the power system in Taiwan will no longer be characterized by the previously recognized “south- to-north” power transmission. Instead, the situation would be changed to various scenarios, including “south and north-to-central” or “north-to-central” transmission at off-peak hours and “central-to-north and south” transmission during peak hours. The status of power transmission in Taiwan would be affected by connection of new power sources (the 4th nuclear power plant, state-owned and private wind farms, *etc.*) into the system and thus expected to undergo further changes in the future.

The study assumes that Type C DFIG (double-fed induction generator) wind turbines, a mainstream product in the market, are used in the offshore wind farm. This type of wind turbine is equipped with a rated real power of 3.6 MW, a cut-in wind speed of 3.5m/s, a rated wind speed of 14m/s, a cut-out wind speed of 27m/s, and a rated voltage of 4.16 kV. Moreover, in steady-state situation, the wind turbine is capable of operating in two modes: power factor control and voltage control.

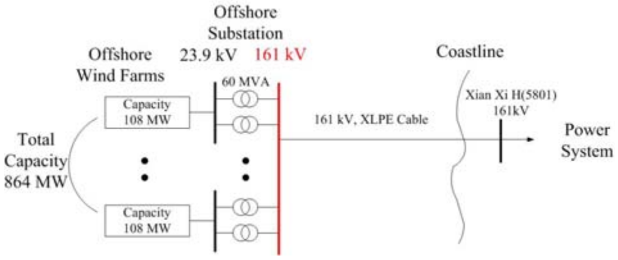

Fig. 1. Single-point connection method (161kV).

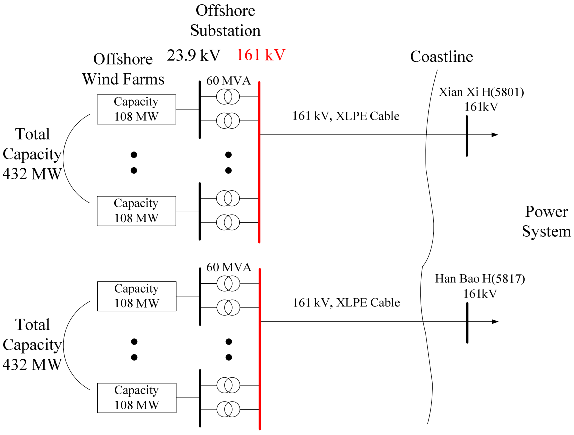

Fig.2 separate-point connection method.

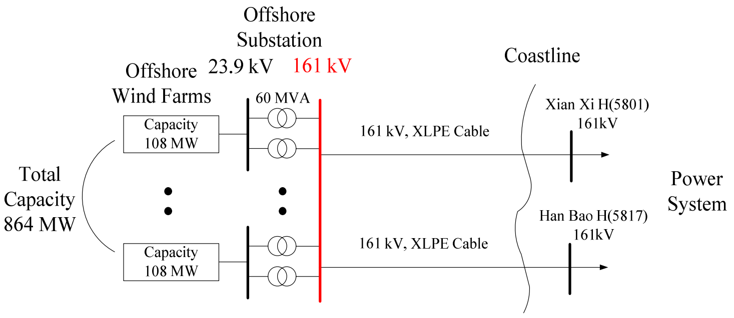

Fig. 3. Multiple-point connection method.

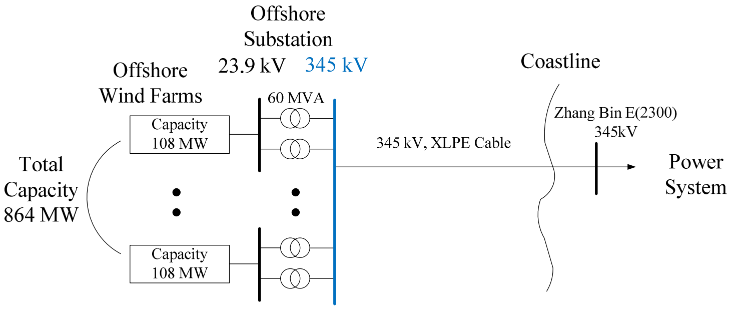

Fig.4. Single-point connection method (345kV).

3. Protection Relay Settings for the Wind Turbines in This Study

As wind power accounts for an increasing percentage, more and more attention has been directed to the impacts of large wind farms on the power system stability. Therefore, the United States and several European countries have revised regulations concerning the operation of wind turbines in the grid codes [6], such as setting more rigorous requirements for connection techniques, regulating the voltage and frequent range for the continuous operation of wind turbines, and demanding wind turbines to be equipped with low voltage ride through (LVRT) ability [7]. In setting the protection relays for the adopted wind turbines, this study has consulted *Technical Rules of Renewable Energy Generation Connected to Taipower Transmission and Distribution Systems* [8]. According to related regulations, wind turbines connected to a 25 kV (or above) system needs to sustain the LVRT ability so as to keep the wind turbines in operation when the system occurs faults. Major technical rules in this study are illustrated by Figs.5-6. Fig.5 shows the LVRT curve in current Taiwan’s grid code, and Fig.6 indicates the continuous operation range on frequency for the protection relay.

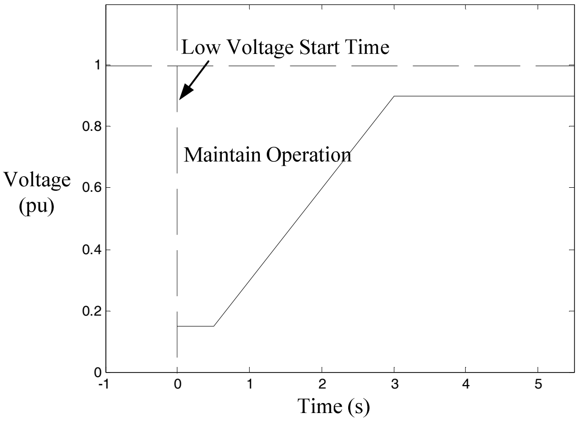

Fig. 5. LVRT requirement in Taiwan.

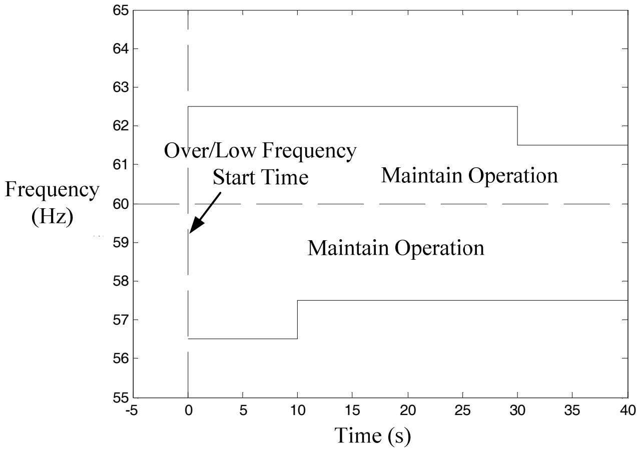

Fig.6. Continuous frequency operation range.

4. Steady-State Analysis

4.1. Power flow analysis

The section analyzes the power flow after the wind farm is connected to the Taipower system, assuming that the wind farm operates at the rated and fixed wind speed for full-load power generation. Under normal condition, when the transmission lines are overloaded after the connection of the wind farm into the power system, the number of transmission lines needs to be increased or the lines changed to sustain a higher rated capacity. Table 1 summarizes the simulation results for steady-state power flow: in the scenario of 345 kV single-point connection, no transmission lines in the Zhang Bin extra high voltage area are overloaded, since the power generated by the wind farm flows into the power system directly from the 345 kV lines, bypassing the 161 kV lines in that area. By contrast, when 161 kV lines are used to connect between wind farm and the grid, and the wind farm is operating for full-load power generation during peak hours, then overloading occurs in all three scenarios of 161 kV connections. Two lines are overloaded based on the 161 kV single-point connection method, while 161 kV separate-point and 161 kV multi-point connection each has one line overloaded.

Table 1. Simulation results of steady-state power flow analysis at peak hours

Connection method	Simulation Results
161 kV Single-point Connection	2 overloaded lines (the branch connecting Fusing H-5855 and Cao Gang bifurcation H-7710 and the branch connecting Cao Gang bifurcation H-7710 and Zhang Bin H-2301).
161 kV Separate-point Connection	1 overloaded line (the branch connecting Fusing H-5855 and Cao Gang bifurcation H-7710).
161 kV Multi-point connection	1 overloaded line (the branch connecting Fusing H-5855 and Han Bao H-5817).
345 kV Single-point Connection	No overloaded line

4.2 Analysis on the maximum three-phase short-circuit current

The main purpose of analyzing fault current is to examine whether the interrupting capacity of circuit breakers in the system is enough to interrupt the maximum fault current. According to the Taipower interconnection rules, the maximum short-circuit currents for the 345 kV and 161 kV systems are respectively 63 kA and 50 kA. Table 2 lists the simulation results: in the scenario of 345 kV single-point connection, the entire wind farm is connected through the Zhang-Bin bus; thus the increase in short-circuit current in this scenario is accordingly greater than those in other scenarios. If the Xien Xi bus and Han Bao bus occur grid faults, an obvious increase in short-circuit current can be observed in the multiple-point connection since a circuit loop is formed inside the wind farm between the two buses. Though still under the cap of 50 kA as stipulated in the Taipower standards, the results suggest the need to pay more attention to the values of breaking current in subsequently installed breakers in the scenario of 161 kV multi-point connection method.

Table 2. Steady-state maximum three-phase short-circuit current simulation results

Location of Short-Circuit Bus	Connection Method	Maximum Three-Phase Short-Circuit Current (kA)
Zhang Bin H-2300	161 kV Single Connection	45.9792
	161 kV Separate Connection	45.9672
	161 kV Multi-connection	45.9801
	345 kV Single Connection	47.0824
Xien Xi H-5801	161 kV Single Connection	43.2481
	161 kV Separate Connection	42.4877
	161 kV Multi-connection	44.9412
	345 kV Single Connection	40.2641
Han Bao H-5817	161 kV Single Connection	24.0258
	161 kV Separate Connection	25.3750
	161 kV Multi-connection	39.9804
	345 kV Single Connection	23.5273

Note: Prior to the wind farm connection, the maximum three-phase short-circuit currents read respectively 45.3092 kA, 39.9723 kA, and 23.4906 kA for Zhang Bin, Xien Xi, and Han Bao buses.

5. Dynamic Analysis

This section examines the transient stability of the Taipower 345 kV bus when the system experiences grid faults, assuming that the wind farm operates at the rated and fixed wind speed for full-load power generation. It is further assumed that the wind farm operates with a controlled power factor of 1.0, and three-phase short-circuit faults take place in the 345 kV Zhang Bin E-2300 bus. The fault is cleared after 6 cycles. Under the above simulation scenario, this study proceeds to analyze the frequency and voltage responses on the Xien Xi bus. The simulation results during off-peak hours are summarized in Tables 3 and 4. Taking the Xien Xi bus as an example, in the scenario of 161 kV single-point connection, since the wind farm is connected to the Xien Xi bus, the wind farm is able to perform direct regulation at this connection point. The voltage drop at Xien Xi bus is therefore less drastic than those in other connection scenarios. Frequency, on the other hand, is under greater influence in the single-point connection; the range of frequency swing at the Xien Xi bus is accordingly greater than those in other connection scenarios.

Table 3. Simulation Results –Transient Voltage Stability at Xien Xi Bus

Connection Method	Voltage drop between initial and lowest voltages
161 kV Single Connection	0.9201 pu
161 kV Separate Connection	0.9284 pu
161 kV Multi-connection	0.9297 pu
345 kV Single Connection	0.9284 pu

Table 4. Simulation Results –Transient Frequency Stability at Xien Xi Bus

Connection Method	Range of Frequency Swing
161 kV Single Connection	59.7902~60.8114 Hz
161 kV Separate Connection	59.7903~60.6659 Hz
161 kV Multi-connection	59.7904~60.6437 Hz
345 kV Single Connection	59.7937~60.1199 Hz

6. Analysis on the Critical Clearing Time (CCT)

Different from those in other countries and regions, the power system in Taiwan is an isolated one characterized by a high density and a north-south longitudinal direction. Though Taipower has built three north-south extra high-voltage power transmission lines, major accidents may still cause problems in transmission stability. This section accordingly focuses on the system's critical clearing time, a key index of transient stability, examining whether the system is able to sustain balance and normal operation after experiencing grid faults and using the result as a yardstick to measure the increase or decrease in critical clearing time. According to the Taipower regular practice of unit dispatch during off-peak hours, in order to avoid load shedding of low-cost generators and the limit by the minimum operating time of some generators, the Taipower' s pumped storage power plants in Mingtan and Daguan play a crucial role in load shedding. As a result, there exists a greater difference in the rotor angle between the generators in South Taiwan and in North Taiwan, making transient stability a more serious problem during off-speak operation. Based on the Taipower system planning experience, when any new generator is installed, system transient stability at off-peak operation must be evaluated. If the system's transient stability meets the required standards, there will be no problem either during peak operation.

Assuming that the wind farm operates at the rated and fixed wind speed for full-load power generation, this section examines the impacts of the wind farm's connection to the power system on the critical clearing time in different connection scenarios. In this study, it is assumed that the Zhang Bin bus appears grid fault and then one of the lines between H-2300 bus and E-540 bus in Zhang Bin area trips offline.

According to a previous study [9], the critical clearing time of a power system could be directly related to the volume and direction of power transmission and the grid topology. The greater the volume of transmitted power, the longer the critical clearing time. Additionally, different connection scenarios would result in different volume and direction of power transmission. Simulation results on CCT are summarized in Table 5, which indicates the CCT in all connection scenarios is twice longer than the CCT requirement in Taipower standard. Compared to the system without the offshore wind farm, the 161kV single-point connection with the wind farm has an increase in critical clearing time while the 161 kV multi-point connection facilitates a decrease in critical clearing time.

Table 5. Critical Clearing Time during off-peak hours

Connection Method	Critical Clearing Time (Cycle)
Wind Farm has not connected yet	12.3672
161 kV Single-point Connection	12.4688
161 kV Separate-point Connection	12.4219
161 kV Multi-point connection	12.2891
345 kV Single-point Connection	12.3672

7. Conclusions

The study focuses on the connection of the Zhanghua Offshore Wind Farm (with a scheduled capacity of 864 MW) into the Taipower system to perform various steady- and dynamic-state simulations and analyses. Major issues under examination include power flow, fault current, system transient stability, and critical clearing time. Impacts of these issues on the power system under different connection scenarios are simulated and analyzed.

In steady-state analyses, the 345 kV single-point connection demonstrates a better performance because all existing transmission lines are not overloaded after the connection of the wind farm. In addition, based on our results, the wind farm is capable of bringing more short-circuit current when the system appears faults. The value of fault current would be determined by the connection location of the wind farm. In dynamic analyses, when grid faults take place, the 161 kV single-point connection reports a smaller voltage drop but a greater range of frequency swing than the other three connection scenarios. In terms of critical clearing time, all simulation results appear to be over twice longer than the requirement of the Taipower standard.

In future development of large-scale offshore wind farms, the above simulation results can be expected to provide Taiwan power system with valuable reference for selecting the proper method of connecting a wind farm to the power system so as to reduce the system steady- and dynamic-state impacts.

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