EVALUATION ON THE EFFECT OF THE INTEGRATION OF OFFSHORE WIND FARMS ON POWER QUALITY

Xin-gang YANG,
East China EPRI – China
xingangyang@gmail.com

Qin-chang GUI
East China EPRI – China
dsy_guiqc@ec.sgcc.com.cn

Ai-qiang PAN
East China EPRI – China
dsy_panaq@ec.sgcc.com.cn

ABSTRACT

The present work analyzed the mechanisms of the harmonic and the voltage fluctuation caused by the grid integration of wind farm. According to the IEC and Chinese national standards, the method and procedure for evaluating power quality of the grid with wind farm connected were formulated, including collection of basic information, determination of bound values of power quality, configuration of simulation network, establishment of mathematical model, and calculation and verification of power quality indexes. The application of the method to an offshore wind farm project in China was demonstrated. The harmonic currents injected into the grid by the offshore wind farm and the levels of the voltage fluctuation generated on the grid common connection-node under various operation conditions were obtained, and the suggestions for improving the power quality were accordingly made. The present work also analyzed the balance of reactive power as well as the feasibility of safety measures after the wind farm was disconnected from the grid and operated under emergent power supply condition, and put forward the reactive power compensation scheme and the control strategies for offshore wind farm operating under emergency. The proposed method and the case study in the present paper certainly have referential values to similar offshore wind farm projects.

0 INTRODUCTION

The effect of grid-integrated wind farms on grid power quality has been attracting increasing concerns of both wind power operators and power grid companies. Power electronic converters of wind turbines injecting harmonic currents to the grid will cause harmonic distortion of the grid bus voltage. The output power fluctuation of wind farm due to wind speed variation and the inherent characteristics of wind turbines, e.g., wind shear, tower shade effect, variation of blade gravity and yaw error, may cause the grid voltage fluctuation and further lead to flicker[1]. Therefore, it is of the practical significance to investigate the power quality issues caused by grid-connected operation of wind farm.

1 MECHANISMS OF POWER QUALITY PROBLEMS CAUSED BY GRID-INTEGRATED WIND FARMS

1.1 Harmonic

For different types of wind turbines, while the harmonic produced by the generators are almost negligible, the real sources of the harmonic are the power electronic components of the wind turbines.

For a double-fed asynchronous wind turbine, the generator stator is directly connected into the grid while the rotor is connected into the grid through two converters linked by DC-link. A directly driven synchronous wind turbine feeds the power into the grid through a back-to-back full power transducer. No matter what type of wind turbine considered, the converter is always working under operation. As a result, the grid-connected operation of a variable-speed wind turbine may result in harmonic problems.

1.2 Voltage Fluctuation and Flicker

The fundamental reason for the wind power causing voltage fluctuation and flicker is the fluctuation of the output power of the grid-connected wind turbine. The grid connection of a wind turbine is schematically shown in Figure 1.

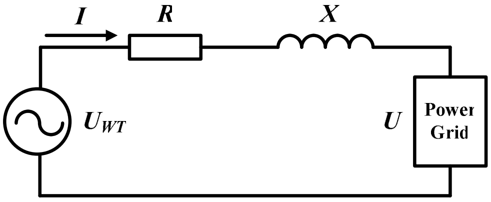

Figure 1 Diagram of a wind turbine connected into the power grid

In Figure 1, U_{WT} is the voltage of the wind turbine, U is the voltage of the power grid, R and X are the equivalent resistance and reactance of lines and transformers, and I is the current of the grid-connected system.

Given the output active and reactive power of the wind turbine are P and Q, respectively, then

$$U = U_{WT} - \frac{PR + QX}{U_{WT}} \tag{1}$$

It can be seen from Equation 1 that the fluctuation of the unit output power will cause the voltage fluctuation and then the flicker of the power grid.

2 EVALUATION METHOD FOR POWER QUALITY OF GRID-INTEGRATED WIND

FARMS

2.1 Evaluation Method for Harmonic

2.1.1 IEC Method

IEC 61400-21 presents a method for calculating the harmonic current resulting from multi wind turbines connected to the point of common coupling (PCC) [2].

$$I_{h\Sigma} = \beta\sqrt[\beta]{\sum_{i=1}^{N_{wt}}\left(I_{h,i}/n_i\right)^{\beta}} \qquad (2)$$

where N_{wt} is the number of the wind turbine connected to the PCC, $I_{h\Sigma}$ is the h^{th} harmonic current distortion at the PCC, n_i is the transformer ratio at the i^{th} wind turbine, $I_{h,i}$ is the h^{th} harmonic current distortion of the i^{th} wind turbine, and β is an exponent with a numerical value given in Table 1.

Table 1 Specification of β value

Harmonic order	β
$h<5$	1.0
$5 \le h \le 10$	1.4
$h>10$	2.0

2.1.2 Chinese National Standard Method

The superposition method for harmonic currents caused by multi wind turbines can also refer to the processing method defined by Chinese national standard [3]. According to GB/T 14549-1993, the same order harmonic currents of two harmonic sources are additive at the same phase. When the phase angle is known, the h^{th} harmonic current is calculated by

$$I_h = \sqrt{I_{h1}^2 + I_{h2}^2 + 2I_{h1}I_{h2}\cos\theta_h} \qquad (3)$$

where I_{h1} is the h^{th} harmonic current of harmonic source 1, I_{h2} is the h^{th} harmonic current of harmonic source 2, and θ_h is the phase angle between the h^{th} harmonic currents of the two sources.

When the phase angle is unknown, the h^{th} harmonic current is calculated by

$$I_h = \sqrt{I_{h1}^2 + I_{h2}^2 + K_h I_{h1} I_{h2}} \qquad (4)$$

Where, the coefficient K_h can be chosen from Table 2.

Table 2 Specification of K_h value

Harmonic order	K_h	Harmonic order	K_h
3	1.62	11	0.18
5	1.28	13	0.08
7	0.72	9，>13, even order	0

When the number of the harmonic currents is more than two, two harmonic currents are added firstly, then the result is added by the third harmonic current, and so on.

2.2 Evaluation Method for Voltage Fluctuation

Voltage fluctuation d is defined as

$$d = \Delta U / U_N \times 100\% \qquad (5)$$

where ΔU is the difference between two adjacent extreme voltages on voltage root-mean-square curve and U_N is the system nominal voltage. The single voltage fluctuation of the wind turbine can be estimated by the system and load parameters.

When the variations of the active power ΔP and reactive power ΔQ of the load are known, the voltage fluctuation d can be calculated by

$$d = \left(R_L \Delta P + X_L \Delta Q\right)/U_N^2 \times 100\% \qquad (6)$$

where R_L and X_L are the resistance and reactance of the power grid, respectively.

In high voltage power grid, $X_L >> R_L$ is generally applicable, therefore

$$d \approx \Delta Q_i / S_{sc} \times 100\% \qquad (7)$$

where S_{sc} is the short circuit capacity of the PCC.

When multi wind turbines are connected to the same PCC, the overall variation of the reactive change can be calculated by the following empirical formula

$$\Delta Q_{\Sigma} = \sqrt[4]{\sum \Delta Q_i^4} \qquad (8)$$

Consequently, Voltage fluctuation d at the PCC resulting from multi wind turbines connecting can be calculated by

$$d = \sqrt[4]{\sum_{i=1}^{N_{wt}} \Delta Q_i^4} \Big/ S_{sc} \qquad (9)$$

3 DETERMINATION OF POWER QUALITY LIMITIS

3.1 Harmonic Limits

According to GB/T 14549-1993, the harmonic current limits of a certain customer injecting into the PCC is calculated by

$$I_h = \left(S_{k1}/S_{k2}\right) I_{hp} \left(S_i/S_T\right)^{1/\alpha} \qquad (8)$$

where I_h is the h^{th} harmonic current limit, S_{k1} is the short-circuit capacity of the PCC, S_{k2} is the datum short-circuit capacity defined in GB/T 14549-1993, S_i is the agreement capacity of the customer, and S_T is the power supply capacity.

Table 3 Harmonic current limit of 110kV grid (A)

Harmonic Order	Harmonic Limits	Harmonic Order	Harmonic Limits
2	12	13	3.7
3	9.6	15	1.9
5	9.6	17	2.8
7	6.8	23	2.1
11	4.3	25	1.9

For 110kV grid, datum short-circuit capacity is 750 MVA.

3.2 Voltage Fluctuation Limits

According to Chinese national standard GB/T 12326-2008[4], voltage fluctuation limits resulting from the load fluctuation at PCC are given in Table 4.

Table 4 Voltage fluctuation limits

r,h^{-1}	d,%	
	U_N≤35kV	U_N>35kV
$r\le1$	4	3
1<$r\le10$	3	2.5
10<$r\le100$	2	1.5

100＜***r***≤1000	1.25	1

4 CASE STUDY

The present work takes wind farm D, a large-scale offshore wind farm in China, as an example to analyze its influence on the grid power quality after its connecting into the grid.

4.1 Basic Data Collection

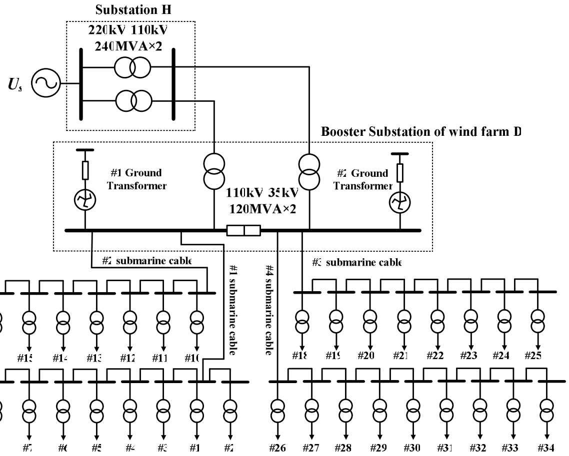

Figure 3 Wiring diagram of wind farm D

Wind farm D is installed with 34 double-fed wind turbines. Each wind turbine has a capacity of 3.1MW.

The harmonic characteristic of the six-impulse current converter on grid side is listed in Table 5.

Table 5 The harmonic characteristic of the converter

Harmonic order	Odd order (%)	Even order (%)
h<11	4.0	1.0
11<***h***<17	2.0	0.5
17<***h***<23	1.5	0.4
23<***h***<35	0.6	0.2
35<***h***<50	0.3	1.1
THD	<5.0	

4.2 Results of Power Quality Calculation

4.2.1 Calculation Modes

Two typical operation modes of wind farm D is Considered:

(1) **Normal Mode**: The 35 kV buses in wind farm D are operated under sectionalizing.

(2) Maintenance Mode: Considering the situation for faults or the planned maintenance, all wind turbines are connected to the grid by one 110 kV cable while the other is idle, the 35kV bus section switch.

4.2.2 Harmonic Results

The results of harmonic currents are shown in Table 6.

Table 6 Harmonic currents injected into 110kV bus in substation H (A)

Harmonic Order	Normal mode	Maintenance mode	Harmonic Limits
2	1.13	1.44	18.96
3	0.02	0.03	11.42
5	4.16	4.37	12.04
7	1.30	1.36	9.26
11	0.33	0.34	6.54
13	0.20	0.21	5.74
15	0.02	0.03	3.00
17	0.03	0.04	4.42
23	0.05	0.08	3.32
25	0.06	0.11	3.00

Because a large portion of the harmonic current emitted from the wind turbine has already been absorbed by the capacity banks of the wind turbines and the earth capacitor of the 35 kV submarine cables, harmonic currents injected into the 110 kV bus of substation H are far less than the limits.

4.2.3 Voltage Fluctuation Results

The results of voltage fluctuation on 110kV bus in substation H are shown in Table 7.

Table 7 Voltage fluctuation on 110kV bus in substation H (A)

Normal Mode	Maintenance Mode	Voltage fluctuation Limit
0.39	0.47	1

It can be found that, even under the most severe condition, the voltage fluctuation on the 110 kV bus of substation H caused by wind farm D is generally under the limit.

4.3 Reactive Compensation Scheme for Emergency Power Supply

In strong typhoon season, all wind turbines need to be forced outage for safety. However, the auxiliary power supplies for the wind turbine head-rotating are supplied by the booster transformer. If wind farm D happens to be isolated from the grid, a 400kW diesel generator is selected to be used as the emergency power supply.

Because the diesel generator has no capability of leading phase operation, the shunt reactor must be installed on the 35kV bus in the wind farm to absorb the charging reactive power of the submarine cables.

In order to reduce the capacity of the reactor to the largest extent, the rotary operational mode is suggested. It means that, at the same time, the 400 kW diesel generator only supplies wind turbines connected to one of the four submarine cables.

To satisfy the operational constraint of the diesel generator, the shunt reactor should be designed into two racks, a basic rack for #1, #2 and #3 cables, and an additional rack for #4 cable.

Table 8 Reactor configuration scheme for wind farm D

Submarine Cable Connected	Reactor in Operation
#1	1200
#2	1200
#3	1200
#4	1200+250

5 CONCLUSIONS

The present work analyzed the mechanisms of harmonic and voltage fluctuation resulting from the grid integration of wind farm. The calculation method and procedure were presented and applied in a Chinese offshore wind farm project. The theoretical analysis and case study showed that:

(1) The operation of wind turbines with power electronic equipments will inject harmonics into the grid. It should be paid sufficient attention on during the design, construction and operation of wind farm. It is also necessary to be calculated and evaluated during design stage. If the harmonic caused by wind farm exceeds the limits, filter device need be installed.
(2) The wind turbine in operation can produce periodical output power fluctuation, leading to the voltage fluctuation of the PCC. The value of voltage fluctuation is related to the characteristics of wind turbine, the grid structure and the short-circuit capacity of the PCC. Installation of dynamic reactive power compensation equipment can decrease the grid bus voltage fluctuation caused by wind farm.
(3) The influence of typhoon on the operation of offshore wind farm should be fully considered. In case the wind farm is isolated from the power grid, it is very necessary to equip a certain capacity of emergency power source, meanwhile to evaluate the influence of the submarine cable charging reactive power on the practical power source and, when necessity, to install inductive reactive power compensation equipment and formulate corresponding operation strategy.

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