Simulation analysis and suppression measures of harmonic resonance of offshore wind farm

YAN Quanchun¹,², GU Wen¹, LIU Yanan¹, LI Chenglong¹, WU Tao¹

¹ Jiangsu Fangtian Electric Power Technology Co., Ltd, Nanjing, 211100, China
² Energy and electrical College of Hohai University, Nanjing, 210098, China
Corresponding author’s e-mail: yanquanchun@hhu.edu.cn

Abstract. Large-capacity long-distance offshore wind farm adopts high-voltage AC submarine cable outgoing line and collecting system. Due to the high capacitance of submarine cable to ground, the harmonic resonance problem of wind farm is increasingly prominent. First of all, through the actual measurement of the wind turbine yaw system exiting due to the 5th harmonic resonance when the wind turbine is shut down in an offshore wind farm along Jiangsu coast, and the analysis of harmonic current and impedance frequency, the reason of resonance is further analyzed. Finally, the ETAP simulation software is used to analyze the measured data, and then several kinds of causes of offshore wind power resonance are obtained, and the corresponding improvement measures are put forward.

1. Introduction
In recent years, offshore wind power has developed rapidly under the support of national policies. Large capacity offshore wind farms have been put into operation intensively. When the long-distance AC offshore cable is used to connect the inductive components of offshore wind farms, parallel resonance is easy to occur, and the resonance problem is more prominent when the cable and transformer are connected. When the parameters of the cable, transformer and overhead line are not well matched, the series resonance is easy to occur. Therefore, it is of great practical significance to study the resonance of offshore wind farms.

At present, offshore wind turbines mainly adopt two types of wind turbines: doubly fed wind turbines and direct drive wind turbines, both of which have bidirectional converters. The yaw system also uses frequency converters to achieve accurate power control adjustment. The power electronic rectifying and inverting components in converters or frequency converters are easy to produce harmonics and inter harmonics, and the main harmonic components are odd harmonics of 3, 5, 7, 11 and 13 [1-5]. At the same time, the harmonic problem of wind farm caused by the system side harmonic invasion also occurs from time to time, which brings great difficulties to the operation and maintenance of wind farm [6-9].

In order to solve the above problems, some literatures mainly use simulation modeling analysis and harmonic sensitivity method based on resonance theory. All of the above methods are lack of test and analysis of the actual wind farm, and there are no literature reports based on the existing harmonic measurement data. The reason of harmonic resonance in offshore wind farm is complex. Based on the tripping fault of yaw system switch caused by wind turbine side harmonic in a real wind farm in Jiangsu Province, this paper uses the measured data of different operating conditions of wind farm to
simulate and analyze the resonance, and puts forward the measures to improve the resonance of wind power. Finally, the simulation results based on ETAP data verify the effectiveness of the proposed suppression measures.

2. Harmonic measurement and analysis of an offshore wind farm

There are 38 sets of Shanghai Electric Siemens 4MW direct driven fans installed in a coastal wind farm in Jiangsu Province, with a total installed capacity of 152MW. Each fan is boosted to 35kV by 0.69/35kv wind turbine transformer, and connected to the 35kV bus of the offshore booster station through six 35kV submarine cable collection lines of different specifications and lengths in chain topology, and then it is boosted to 110kV by a 160MVA, 35/110kV transformer. It is transmitted to the land booster station through two 110kV 28.5km submarine cables. After boosting to 220kV, it is connected to the power grid through an 8.91km overhead line. The main electrical wiring is shown in Figure 1. A 150 MVA three coil transformer is installed in the substation. The voltage on the three sides of the main transformer is 220/110/35kV. Two shunt reactors, one field transformer and one SVG are installed on the 35kV side (long-term outage due to fault).

![Figure 1. Diagram of offshore wind farm wiring mode](image)

2.1 Fan failure

From April to September of 2019, there were 11 large-scale failures of wind turbines in the offshore wind farm, and no fault occurred after October. The specific situation is as follows: when the fault occurs, the wind condition is light wind or no wind, and the wind turbine is in the state of waiting for wind (all are not connected to the grid). When the wind increases to the starting wind speed, the operators find that the wind turbine yaw system can not work, and the maintenance personnel arrive at the offshore wind turbine platform after more than 2 hours of sea voyage, and all or most of the circuit
breakers of the wind turbine yaw system trip. Since the circuit breaker has no alarm and can not automatically switch on after tripping, the fault situation and occurrence time are unknown, so it is necessary to manually recover one by one fan, which brings great trouble to the wind farm power generation, safe operation and maintenance of wind turbine.

During this period, the wind farm access to the grid changed as follows: before May, the wind farm was connected to switch station with a single 220kV line; in May, the line from the wind farm to switch station a was disconnected and connected to switch station B; from May to October, only two lines were connected to switch station B; on October 26, two 220kV lines were added to switch station C (500kV switching station); in November, one 220kV line was added to switch station a.

Operation analysis shows that if several wind turbines in the wind farm are still connected to the grid, even if the generating power is very small, there will be no large-scale fault of the above-mentioned fans.

2.2 Fan fault cause search
The fan yaw system is located in the engine room and is composed of contactor, autotransformer (690 / 460V), circuit breaker F1 (range 45-63A, set as 57A, trip if 57A lasts for 7s), reactor, yaw frequency converter and yaw motor. The fault is caused by the tripping of circuit breaker F1. The power supply of the yaw system is taken from the 690V side of the fan transformer, which is completely independent of the wind turbine power generation system. When the fan is waiting for wind, the generator inverter filter system is disconnected from the 690V side of the fan transformer through the low-voltage circuit breaker, while the yaw system continues to operate.

A fan is selected to test the wind farm and yaw system under different working conditions. Test point 1 is the power supply side of the circuit breaker F1 of the yaw system, and test point 2 is the low voltage side of the fan transformer. The test was carried out by the fan manufacturer. Due to the limited conditions, the two test points could not be tested at the same time, and all working conditions and data were not included.

It is found that the voltage and current of the two test points contain rich harmonic components, and the fifth harmonic is the largest, which accounts for the majority of total harmonic voltage distortion (THDu) and total harmonic current distortion (THDi). Refer to the test results of the frequency converter, such as the frequency converter of the odd side, the third side, the third side, the third side and the third side of the inverter are not consistent with the test results.

Table 1. Harmonic test of wind turbine under different operation state at low voltage side of wind turbine transformer

| working condition (wk) | THD (%) | THDi (%) | Current (A, True RMS) | 5th harmonic current (A) |
|------------------------|---------|----------|----------------------|-------------------------|
| wk1                    | 0.92    | 5.76     | 926                  | 46.795                  |
| wk2                    | 14.91   | 26.05    | 27                   | 6.773                   |
| wk3                    | 14.16   | 106.28   | 67                   | 46.688                  |

Condition 1: generating power in the whole site, testing fan yaw; condition 2: Fan waiting for wind in the whole site, test fan stopped without yaw; condition 3: all fans waiting for wind, test fan stopped, yaw.

Analysis of the test data under different working conditions has the following characteristics: 1) when the fan is waiting for wind, the circuit breaker F1 current exceeds the circuit breaker action current, and the cause of circuit breaker F1 tripping can be basically determined; 2) the harmonic voltage is basically normal when the whole field power generation and some fans generate power; when the whole fan is waiting for wind, the harmonic voltage distortion increases greatly; 3) the yaw current of the fan is greater than that of the non yaw fan 4) compared with conditions 1 and 3 in Table 2, the fifth harmonic current is about 46a, but the fifth harmonic current may include the fifth harmonic current from the generator.
In Table 2, the harmonic voltage distortion at the low-voltage side of the fan transformer does not correspond to the harmonic current value, for example, the harmonic current of the 1st, 3rd and 5th working conditions is similar, but the harmonic voltage distortion is quite different; under working conditions 2 and 3, the harmonic voltage distortion is similar, but the 5th harmonic current is quite different. If the wind turbine is used as the harmonic source, even if the 5th harmonic current of 46a is injected into the low-voltage side of No.38 fan and added algebraically, the 5th harmonic current of 35kV side is about 35A, which can not produce such large harmonic voltage distortion at 35kV.

The fifth harmonic resonance should occur in the analysis, but not in the fan side, but in the superior system, the fifth harmonic voltage distortion comes from the superior power supply.

2.3 Harmonic measurement and analysis of Lu ascending voltage station

Online power quality monitoring devices are installed at the public connection point (switch station a) and merging point (land booster station) of the wind farm to monitor the 220kV lines of the wind farm connected to the power grid. However, the monitoring point a of the switch station only has the data of April. Comparing the April data of the two test points, it is confirmed that the fifth harmonic is abnormal when the wind turbine of the wind farm is waiting for wind. Take April 15 as an example, the most stringent one is taken The maximum 95% probability of the 5th harmonic current of 220kV line is 67.87A and the maximum value is 71.41A. The 5th harmonic voltage content and thd at the junction point are 1.66%. The 5th harmonic voltage and current are basically normal under other operation conditions of wind farm. The maximum 95% probability maximum value of the 5th harmonic current of 220kV line is 3.36A, the maximum value is 3.6A, and the 95% probability maximum value of the fifth harmonic voltage content at the connection point is 1.09% and 1.12% respectively.

For more detailed and accurate research and analysis, a power quality analyzer meeting the requirements of IEC 61000-4-30 class A is installed in the substation. In order to ensure the simultaneity, one phase is taken from each side of the main transformer. Through the continuous test from August to September, six abnormal events were found, two of which were serious, and large area faults occurred in all fans. Take September 3-4 as an example

![Trend chart of single phase active power distortion](image-url)

a. Trend chart of single phase active power distortion
The curves of normal harmonics before and after September 3-4 are reserved in Figure 2 for comparison. The blue, red and green curves represent the three sides of the main transformer, respectively. The magnitude of active power on 220kV side and 110kV side is the same, but the direction is opposite because it is outflow and inflow of main transformer respectively. The 35kV side is reactive power compensation equipment and field transformer, and the active power is very small. The fifth harmonic voltage and current are very small when the wind turbine of wind farm is connected to the grid, while the active power is close to zero while the fifth harmonic voltage and current increase greatly; the maximum fifth harmonic current of 110kV side is more than 120A, which is about twice of that of 220kV side, indicating that the fifth harmonic current of 220kV side is almost injected into (or comes from) 110kV side, and the fifth harmonic voltage of 35kV side is equal to 110kV side. The same shows that the increase of harmonic current from 110kV side is due to the large increase of harmonic voltage distortion; during the period of fan waiting for wind, the 5th harmonic voltage content of 220kV side is 2%, the content of 5th harmonic voltage on 110kV side is more than 15%, which is far more than 1.6%. The 5th harmonic voltage content of 35kV side of main transformer on land is far more than 2.4%. Under normal conditions, the fifth harmonic voltage content in 220kV system is also high, which is related to the access of a large number of wind farms in the area where the wind farm is connected.
2.4 Opening and closing test of offshore collecting line

In order to determine whether the abnormal harmonic is caused by the system harmonic or the harmonic generated by the wind turbine yaw system is amplified by resonance, the wind farm organized a test to cut and restore the six 35kV collection lines one by one under the condition of no wind according to the wind power prediction. However, the no wind time window is too short, so the opening and closing test can only be carried out quickly in advance. The test personnel did not arrive at the offshore booster station in time. The harmonic test results of 110kV and 35kV system of offshore booster station behind power grid are normal.

In 16 minutes, the operation of removing and resuming six 35kV collecting lines one by one is completed. The variation trend of the 5th harmonic current at 110kV side of the main transformer is shown in Figure 3. The 5th harmonic current decreases with the removal of the collection line and increases with the input of the collection line. Since the measurement interval is 1 minute, the removal and recovery operation is relatively fast, the change step of 5th harmonic current is not very clear, but the trend is obvious; after all the 6 collection lines are cut off, it is kept for 5 minutes (11:50 ~ 11:55 in the figure), at this time, the 5th harmonic current still has more than 60A. Therefore, it can be determined that under the influence of the 5th harmonic voltage of the grid, the 5th harmonic series resonance occurred in the 110kV wind farm system, but the possibility of 35kV system resonance amplification cannot be ruled out.
3. Simulation analysis

In order to analyze the causes of harmonic resonance in wind farm and provide ideas for restraining resonance, ETAP power system analysis software is used for simulation analysis. The software can be used for harmonic power flow analysis and impedance frequency scanning.

According to figure 1, the wind farm simulation system is established, and the collection system composed of 35kV submarine cable and 38 wind turbine is built according to the as built drawing. The system equivalence is carried out in switch station B, which is used as harmonic voltage source. The measured parameters are used for 220kV overhead line and 110kV submarine cable, and factory data and actual length are used for 35kV submarine cable of various specifications. Since the distributed capacitance of 220kV overhead line and submarine cable is the main factor affecting harmonic analysis of wind farm, accurate modeling is adopted as far as possible, and PI is used for line and submarine cable Other equipment, such as transformers and reactors, are modeled according to actual parameters, and their small harmonic voltage influence is ignored. Because only the situation that the fan stops to wait for wind or generates power with very low power is simplified, the model provided by software directly for the fan is not modeled in detail. When the fan stops waiting for wind, only the yaw system operates, which is regarded as the load as harmonic power When the wind turbine generates power at low power (1% capacity in simulation), the wind turbine and yaw system operate in parallel.

3.1 Fan waiting for whole plant

The whole system of the wind farm is running, and the wind turbines are waiting for wind. The B harmonic voltage of the switching station is set as 0. According to the measured value, the second to 25th harmonic currents are input to the low voltage side of each fan transformer, of which the fifth harmonic current is 6.773a and 46.688a respectively.
Table 2: Total harmonic distortion at different buses of offshore wind farm when wind turbine output high and low harmonic current.

| 5th harmonic current of fan (A) | Offshore 35kV THDu (%) | Offshore 110kV THDu (%) | On land 110kV THDu (%) | On land 220kV THDu (%) | Switchyard B 220kV THDu (%) |
|-------------------------------|------------------------|------------------------|------------------------|------------------------|-----------------------------|
| 6.773                         | 0.59                   | 0.68                   | 0.66                   | 0.22                   | 0.21                        |
| 46.688                        | 5.43                   | 6.23                   | 6.01                   | 2.02                   | 1.88                        |

Table 3: 5th harmonic current at different lines of offshore wind farm when wind turbine output high and low harmonic current.

| 5th harmonic current of fan (A) | Marine main transformer 35kV side (A) | Marine main transformer 110kV side (A) | Main transformer on land 110kV side (A) | 220kV line (A) |
|-------------------------------|---------------------------------------|---------------------------------------|----------------------------------------|---------------|
| 6.773                         | 3.5                                   | 1.1                                   | 4.8                                    | 2.4           |
| 46.688                        | 32.7                                  | 9.9                                   | 43.8                                   | 21.7          |

The fifth harmonic current on the 35kV side of the offshore main transformer is basically the sum of the fifth harmonic current of the 38 fan, but the fifth harmonic current of the 110kV system is more than four times of the amplification.

When the background harmonic voltage of the system is 0, the harmonic current and voltage distortion obtained by simulation are far less than the measured values even if the harmonic current at the low voltage side of 38 fan is the maximum. When the system background harmonic voltage is 0.

The background harmonic of the switch station B is estimated according to the measured data, in which the 5th harmonic voltage is 0.75%, THDu is 0.88%, and the 5th harmonic current at the low voltage side of the fan transformer is 6.773A.

Table 4: Total harmonic distortion at different buses of offshore wind farm when wind turbine output low harmonic current.

| 5th harmonic current of fan (A) | Offshore 35kV THDu (%) | Offshore 110kV THDu (%) | On land 110kV THDu (%) | On land 220kV THDu (%) | Switchyard B 220kV THDu (%) |
|-------------------------------|------------------------|------------------------|------------------------|------------------------|-----------------------------|
| 6.773                         | 14.05                  | 12.93                  | 12.01                  | 1.16                   | 0.88                        |

Table 5: 5th harmonic current at different lines of offshore wind farm when wind turbine output low harmonic current.

| 5th harmonic current of fan (A) | Marine main transformer 35kV side (A) | Marine main transformer 110kV side (A) | Main transformer on land 110kV side (A) | 220kV line (A) |
|-------------------------------|---------------------------------------|---------------------------------------|----------------------------------------|---------------|
| 6.773                         | 43.6                                  | 13.2                                  | 122.6                                  | 61            |

The harmonic voltage and current obtained by simulation are very close to the measured data. The impedance frequency scanning is carried out, as shown in Figure 4. There are five curves in total, from top to bottom, they are marine 110kV bus, onshore 110kV bus, onshore 220kV bus, switchyard b220kV bus and offshore 35kV bus. The impedance of onshore 220kV bus and b220kV bus of switching station is the lowest near the 5th harmonic, and the impedance of offshore 35kV bus is also very small. The 5th harmonic impedance is 33.39Ω, 22.48Ω and 22.81Ω, respectively M.
Therefore, the reasons for the abnormal harmonics of the wind farm and a large number of faults of the wind turbine are as follows: under the influence of the fifth harmonic voltage background of the system, the fifth harmonic series resonance occurs, at the same time, the fifth harmonic current generated by the yaw system of the wind turbine is amplified in the 110kV system, and the series resonance is the main factor, which makes the fifth harmonic abnormal in the wind farm and flows through the bias under the serious harmonic voltage distortion. When the total effective current including harmonic current exceeds the action current, the switch will trip.

After October 2019, the wind farm did not have a large number of wind turbine failures when waiting for wind. The analysis is as follows: after October, three 220kV lines are successively connected to the switch station B, of which two are from the 500kV switching station, and the short-circuit capacity increases significantly. The increase of short-circuit capacity does not change the resonance conditions of the wind farm, but the harmonic voltage content of the system is reduced by half; the harmonic voltage of the switch station B is reduced to 0.4% THDu and 0.24% of the 5th harmonic voltage, and then the whole wind turbine waiting is conducted again. The simulation results show that the THDu of 35kV, 110kV and 110kV buses on the sea are 6.17%, 5.60% and 5.19% respectively, and the injected fifth harmonic current of 220kV is 26.8A, which is close to the monitoring value of online monitoring system. Due to the significant reduction of the 5th harmonic voltage of the system, although there is still resonance, the harmonic voltage and current of the wind farm are greatly reduced, which will not cause the switch trip of the wind turbine yaw system.

In the simulation, the switching station B is used as the harmonic voltage source, and the harmonic voltage is fixed, so that the harmonic voltage of the wind farm and the dot is too small; the yaw system on the low voltage side of the fan transformer is regarded as the harmonic current source, and the harmonic current content is constant, and the influence of the increase of harmonic current content under the condition of voltage distortion is not considered.

3.2 Simulate that some fans don’t stop
Wind farm operators found that when a small number of wind turbines continue to operate without shutdown, a large number of fans will not fail. The scenario is simulated, in which 1, 2, 3, 4 wind turbines are not shut down to generate power at 1% rated capacity.
Table 6. Total harmonic distortion at different buses of offshore wind farm when a few wind turbines operate

| Number of fans in operation | Offshore 35kV THDu (%) | Offshore 110kV THDu (%) | On land 110kV THDu (%) | On land 220kV THDu (%) |
|----------------------------|------------------------|-------------------------|------------------------|------------------------|
| 1                          | 10.83                  | 10.11                   | 9.41                   | 1.10                   |
| 2                          | 8.74                   | 8.26                    | 7.71                   | 1.06                   |
| 3                          | 7.30                   | 6.98                    | 6.53                   | 1.03                   |
| 4                          | 6.27                   | 6.08                    | 5.69                   | 1.01                   |

Table 7. 5th harmonic current at different lines of offshore wind farm when a few wind turbines operate

| Number of fans in operation | Marine main transformer 35kV side (A) | Marine main transformer 110kV side (A) | Main transformer on land 110kV side (A) | 220kV line (A) |
|-----------------------------|--------------------------------------|---------------------------------------|----------------------------------------|----------------|
| 1                           | 28.3                                 | 8.4                                   | 93.8                                   | 46.6           |
| 2                           | 22.6                                 | 5.3                                   | 75.0                                   | 37.3           |
| 3                           | 20.3                                 | 3.3                                   | 62.2                                   | 30.9           |
| 4                           | 16.6                                 | 1.9                                   | 52.8                                   | 26.2           |

Figure 5. Simulation diagram of wind farm impedance frequency characteristics when four wind turbines operate

Taking the operation of 4 fans as an example, the impedance frequency diagram of wind farm is observed. The lowest impedance of 220kV bus on land, b220kv in switch station and 35kV at sea is moved from the 5th harmonic to the 6th harmonic. The 5th harmonic impedance is 71.78 ohm, 91.50 ohm and 31.93 ohm respectively. When the foot fan is stopped, the harmonic is greatly reduced.

During the simulation, the four fans are placed in different branches, and the positions in the branches are random, because the actual situation is also random. With the increase of the number of running fans, the harmonic voltage and current also decrease; it is found in the simulation that the position of the running fan in the branch is also an influencing factor, and the closer the 35kV bus is, the better the effect of harmonic suppression is.

3.3 Simulation of collector wire breaking and closing test

Simulation and Simulation of 6-circuit collector wire opening and closing test, all fans in the site are stopped, and the 6-circuit collection line is cut off gradually.
Table 8. Sequential trip and close operations of collecting system, total harmonic distortion at different buses

| Number of cut | Offshore 35kV THDu (%) | Offshore 110kV THDu (%) | On land 110kV THDu (%) | On land 220kV THDu (%) |
|---------------|------------------------|-------------------------|------------------------|------------------------|
| 1             | 11.03                  | 10.29                   | 9.58                   | 1.11                   |
| 2             | 9.61                   | 9.06                    | 8.44                   | 1.08                   |
| 3             | 7.57                   | 7.27                    | 6.80                   | 1.04                   |
| 4             | 6.77                   | 6.57                    | 6.15                   | 1.03                   |
| 5             | 5.71                   | 5.63                    | 5.29                   | 1.00                   |
| 6             | 5.06                   | 5.07                    | 4.77                   | 0.99                   |

Table 9. Sequential trip and close operations of collecting system, 5th harmonic current at different lines

| Number of cut convergence lines | Marine main transformer 35kV side (A) | Marine main transformer 110kV side (A) | Marine main transformer 110kV side (A) | 220kV line (A) |
|-------------------------------|--------------------------------------|---------------------------------------|---------------------------------------|----------------|
| 1                             | 28.5                                 | 8.7                                   | 95.8                                  | 47.6           |
| 2                             | 21.8                                 | 6.6                                   | 83.2                                  | 41.4           |
| 3                             | 11.9                                 | 3.6                                   | 65.2                                  | 32.4           |
| 4                             | 9.1                                  | 2.5                                   | 58.0                                  | 28.8           |
| 5                             | 3.1                                  | 0.9                                   | 48.6                                  | 24.2           |
| 6                             | 0.0                                  | 0.1                                   | 42.8                                  | 21.3           |

The simulation results are basically consistent with the experimental results. The 6-circuit collection line can be regarded as a 6-circuit parallel circuit. Every time one circuit is cut off, the impedance of the parallel circuit increases, and at the same time, the 5th harmonic injected by the fan yaw system of the loop is also reduced, so the harmonic voltage and current are reduced; after all the 6-circuit collection lines are cut off, the impedance frequency characteristic is similar to that in figure 5, and the lowest point of impedance is moved to the 6th harmonic, but the 5th harmonic impedance is still small, and the 5th harmonic impedance is still small. The magnitude of wave voltage and current is determined by the 5th harmonic voltage level and harmonic impedance of the system.

4. Analysis of resonance suppression measures
The suppression of harmonic resonance should be considered from two aspects: harmonic source and resonance condition.

4.1 Resonance check analysis or special research in planning and design stage
With the rapid development of offshore wind power, the long-distance submarine cable AC access mode is used to access the power grid, and the series parallel resonance may be greater under the parameter coordination. When the offshore wind farm is planned to be connected or preliminarily designed, resonance check should be carried out to avoid resonance after putting into operation.

Existing design codes such as gb51096-2015 wind power plant design code, Nb. T. Neither 31003-2011 technical code for grid connected design of large wind power plants nor Q / GDW 1868-2012 design content depth of wind farm access system require verification analysis or special research.

4.2 Suppressing parallel resonance
For wind farm a, harmonics are generated when the wind turbine generates power, but there is a filter in the circuit, and the yaw frequency converter generates harmonics when yawing; it can be considered to add a filter at the power side of the frequency converter (it is optional to refer to the wind turbine data of wind farm a, but it is not configured actually). If the yaw frequency converter adopts controllable rectification mode, the harmonic content will also be significantly reduced.

Due to the limitation of space and weight of offshore booster station and wind turbine platform, as well as the existence of series resonance, it is not feasible to add primary equipment such as parallel filter and shunt reactor to absorb harmonic or change impedance frequency characteristics.
4.3 Suppression of series resonance
For the series resonance, the harmonic level of the wind farm is greatly reduced after switching station B is connected to the two circuit lines from 500kV substation in October 2019. It is effective to reduce the background harmonic voltage at the system side, but it is difficult to control artificially.

Therefore, it is necessary to start from changing the resonance conditions, parallel impedance has no effect. It is simulated that adding shunt reactance at 110kV side of main transformer on land and changing reactor impedance at 35kV side have no effect, while it is difficult to add primary equipment in offshore part of wind farm. It is necessary to change the impedance of the series circuit to suppress the series resonance.

Scheme 1: series reactance of 110kV submarine cable ashore. The simulation results show that under the background harmonic voltage level of the system, each 110kV submarine cable needs to be connected in series with 10 ohm reactance to reduce the THDu of 35kV offshore wind farm and 110kV system to 3.20% during resonance, which is slightly higher than the allowable value of national standard, while the actual impedance of single 110kV submarine cable is less than 4 ohm; the feasibility of operation is not very large, so it is necessary to consider the short circuit of series reactance during normal power generation of wind farm. When resonance occurs, it is necessary to add a device and the operation is troublesome.

Scheme 2: add one 110kV Bay on land and at sea respectively. After transformation, two 110kV submarine cables can be switched independently, and one 110kV submarine cable can be cut off when resonance occurs.

Simulation results show that under the background of system harmonic voltage, the resonance is basically destroyed after the wind turbine is waiting for wind, and the THDu of 35kV and 110kV system is reduced to 3.16%, which is slightly higher than the allowable value of the national standard. Therefore, cutting off the first submarine cable when two or more submarine cables are connected is an effective way to break the series resonance. Among the more than 10 offshore wind farms that have been put into operation in Jiangsu coastal area, only one wind farm adopts single circuit AC submarine cable. The wind farm described in this paper adopts double circuit submarine cable, but it can not be switched separately. Other wind farms all adopt double circuit independent submarine cable.

Table 10. Trip one 110kV submarine cable, total harmonic distortion at different buses of offshore wind farm

| 5th harmonic | Offshore 35kV THDu (%) | Offshore 110kV THDu (%) | On land 110kV THDu (%) | On land 220kV THDu (%) |
|-------------|------------------------|------------------------|------------------------|------------------------|
| 6.773       | 3.32                   | 2.86                   | 2.49                   | 0.90                   |

Table 11. Trip one 110kV submarine cable, 5th harmonic current at different lines of offshore wind farm

| 5th harmonic | 35kV side of marine main transformer (A) | 110kV side of marine main transformer (A) | 110kV side of main transformer on land (A) | 220kV line (A) |
|-------------|----------------------------------------|------------------------------------------|-------------------------------------------|---------------|
| 6.773       | 11.3                                   | 3.4                                      | 11.9                                      | 5.9           |

4.4 Online power quality monitoring system for offshore booster station
At present, as long as the wind farm is required to configure power quality online monitoring device at the merging point, and usually the operation management is not in place, and the parameter configuration is wrong; the offshore booster station of offshore wind farm does not require configuration, so it is difficult to conduct comprehensive analysis after resonance, so the requirements should be put forward.

5. Conclusion
In this paper, the resonance simulation of offshore wind farm is carried out based on the measured data. Through harmonic power flow analysis and impedance frequency scanning, the harmonic resonance
and fault causes of wind turbine are analyzed. Through the comparison between the measured and simulated results, the measured data in several cases are consistent with the simulation results, and it is confirmed that the offshore wind farm has serious problems when the wind turbine is completely stopped. The main conclusions are as follows:

a) Offshore wind power is connected to the power grid by long-distance submarine cable AC connection, which may cause series parallel resonance under the coordination of various equipment parameters.

b) The main reason for the switch tripping of the yaw system when the wind turbine is shut down is that the harmonic voltage is seriously distorted after the resonance of the wind farm, and the total current including harmonic current exceeds the tripping action value of the switch.

c) Although the offshore wind farm adopts double circuit 110kV submarine cable, only one circuit breaker is equipped on both sides. In case of series resonance, the resonance cannot be destroyed by cutting off one circuit 110kV submarine cable. It is suggested that the offshore wind farm with long-distance AC submarine cable should at least adopt the design of double circuit independent submarine cable.

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