The harmonic characteristics analysis of offshore wind farms transmitted by the submarine cable based on time domain simulation

Jingyi Li¹, Jianjun Yang¹, Zhaohui Shi¹, Ke Wang¹, Haozhi Li², Xiaorong Xie², Fangfeng Li¹

¹Key Laboratory of Far-shore Wind Power Technology of Zhejiang Province (Huadong Engineering Corporation Limited, Power China), Hangzhou, Zhejiang, 311122, China
²State Key Laboratory of Control and Simulation of Power Systems and Generation Equipment (Department of Electrical Engineering, Tsinghua University), Haidian District, Beijing, 100084, China

*Corresponding author’s e-mail: li_jy3@hdec.com

Abstract. The harmonic amplitude may exceed the limit when the large scale of wind farm is connected to the weak AC system through AC submarine cable. The harmonic with high amplitude will endanger the safety of power equipment, and even affect the normal integration of large-scale wind farm. This paper takes an actual offshore wind power connected to the system through AC submarine cable as an example. On the basis of building the model of the system in the PSCAD/EMTDC simulation software. The simulation calculation is systematically carried out. The effect of multiple factors on the harmonic characteristics is analyzed. The preliminary explanation for the harmonic amplitude out of limit is given for the actual large scale of wind farm connected to the weak AC system through AC submarine cable.

1. Introduction

When offshore wind power is connected to the weak AC system through AC submarine cable, the problem of excessive harmonics may be induced. At the beginning of 2019, the high-amplitude harmonic was observed in the grid-connected offshore windfarm. This paper takes an actual offshore wind power connected to the system through AC submarine cable as an example. On the basis of building the model of the system in the PSCAD/EMTDC simulation software. The simulation calculation is systematically carried out. The effect of multiple factors on the harmonic characteristics is analyzed. The preliminary explanation for the harmonic amplitude out of limit is given for the actual large scale of wind farm connected to the weak AC system through AC submarine cable.
relative gain matrix, it is pointed out that when the interaction between the two converters is strong, the amplitude of the harmonics is higher. References [8-9] analyze the effects of various factors on the amplitude characteristics of harmonic based on the amplitude-frequency characteristics of the impedance model. In reference [10], based on the obtained impedance model, the superposition calculation method is used to analyze the harmonic amplitude. In the references [4-10], the linearized impedance method is used for revealing the generating mechanism of high amplitude of harmonics for the ideal system. While for the practical system, the changing mechanism for the amplitude of multiple harmonics is unknown.

Reference [11] uses open-loop transfer function to analyze the response characteristics of the converter control system to the inter-harmonics, revealing the coexisting mechanism of the multiple inter-harmonics in the system. Meanwhile, the paper qualitatively analyzes the relative relationship between the amplitudes of each harmonic. However, the open-loop transfer function cannot accurately analyze the harmonic amplitudes because it cannot account for feedback effects. References [12-13] judges the stability of the system based on the pole criterion of closed-loop transfer function. Reference [14] reveals the cause of high amplitude harmonics from the perspective of harmonic amplification based on the amplitude-frequency characteristics of the closed-loop transfer function. However, the focus of references [12-14] are on whether harmonics are generated for the onshore windfarms based on the linearized analytical model. The specific value of the harmonic amplitude is not further paid attention to. The submarine cable with the capacitance to the ground is not considered. For the calculation of the specific harmonic amplitude, the time-domain simulation method will be better than the linearized model which is specified on revealing the generating mechanism of harmonics [15-17].

In this paper, the harmonic amplitude characteristics of an actual offshore wind farm connected to weak AC system through submarine cable is analyzed based on the time domain simulation. The simulation model for the practical system is built. With the model, the problem in the practical system which the harmonic amplitude exceeds the standard is analyzed. The effect of the wind turbine generator (WTG) numbers, the output of the WTG, the AC submarine cable length, and the strength of the grid-connected system on the harmonic characteristics are analyzed. On this basis, a preliminary explanation is given for the harmonic amplitude characteristics of the offshore wind power transmission system through the AC submarine cable.

2. The Grid-Connected Offshore Wind Farms through AC Submarine Cable

The structure of offshore wind power transmission system through AC submarine cable is shown in Figure 1. There are total of 63 permanent magnet synchronous generators and the capacity of each wind turbine is 4MW. 32 wind turbines are connected to bus I and 31 wind turbines are connected to bus II. They are further boosted to 220kV by two 140MW main transformers. Finally, the wind power is connected to the AC system. The system parameters are shown in Table 1 below.

| Parameter name                                      | Parameter value |
|-----------------------------------------------------|-----------------|
| Number of wind turbine generators in the sub-wind farm 1 \( (n_1) \) | 32              |
| Number of wind turbine generators in the sub-wind farm 2 \( (n_2) \) | 31              |

Figure 1 The grid-connected offshore wind farm transmitted through the AC submarine cable

Table 1 The system parameter of the grid-connected offshore wind farm transmitted by the AC submarine cable
3. Wind Turbine Modeling

Due to the isolation of the DC capacitor, the characteristics of the harmonics are mainly related to the grid-side converter. The topology of the grid-side converter control system is shown in Figure 2, which mainly includes the d/q-axis current control system and a phase-locked loop.

\[
\begin{align*}
U_{cd \_ref}^e &= \frac{G}{1 + Ts} U_{dc}^e - (K_{pd} + \frac{K_{id}}{s})(I_{d \_ref}^e - I_d^e) \\
U_{eq \_ref}^e &= \frac{G}{1 + Ts} U_{dc}^e - (K_{pq} + \frac{K_{iq}}{s})(I_{q \_ref}^e - I_q^e) \\
I_{d \_ref}^e &= (K_{pc} + \frac{K_{dc}}{s})(U_{dc \_ref}^e - U_{dc}^e)
\end{align*}
\]

In the above formula, the variables with * are the values in per unit. \(K_{pd}, K_{pq}, K_{id}, \text{ and } K_{iq}\) are the d/q-axis proportion and integration coefficients of the current inner loop. \(K_{pc} \text{ and } K_{dc}\) are the outer loop proportion and integration coefficients. \(U_{cd \_ref}^e \text{ and } U_{eq \_ref}^e\) are the dq axis voltage references in the control system coordinate system. \(U_{dc}^e\) is the measured DC voltage. \(U_d^e, U_q^e, F_d, \text{ and } F_q\) are the bus voltage and bus current components in the d/q synchronous coordinate system. \(G \text{ and } T\) are the proportion and delay parameters of the voltage feedforward link. \(X_L\) is the impedance of the filter inductor.

3.2. Phase-locked loop

The block diagram of the phase-locked loop control system is shown in Figure 3. The main function of the phase-locked loop is to control the phase-locked loop output phase angle \(\theta_{PLL}\) to track the phase of the locked bus voltage \(\theta_L\). It is mainly realized through coordinate transformation and PI control system.
The phase transformation of the phase-locked loop is as follows:

\[
\begin{bmatrix}
U_d \\
U_q
\end{bmatrix} = \mathbf{P}(\theta_{\text{PLL}}) \begin{bmatrix}
U_a \\
U_b \\
U_c
\end{bmatrix}
\]  

(2)

In the above formula, \(U_{abc}\) is the bus voltage component in the ordered coordinate system, \(U_{dq}\) is the bus voltage component in the synchronous coordinate system, and \(\mathbf{P}(\theta_{\text{PLL}})\) is the Park transformation matrix. The PLL model is given as:

\[
\begin{bmatrix}
\cos(\theta_{\text{PLL}} + \frac{\pi}{2}) \\
\cos(\theta_{\text{PLL}} + \frac{\pi}{2} - \frac{2\pi}{3}) \\
\cos(\theta_{\text{PLL}} + \frac{\pi}{2} + \frac{2\pi}{3}) \\
\sin(\theta_{\text{PLL}} + \frac{\pi}{2}) \\
\sin(\theta_{\text{PLL}} + \frac{\pi}{2} - \frac{2\pi}{3}) \\
\sin(\theta_{\text{PLL}} + \frac{\pi}{2} + \frac{2\pi}{3})
\end{bmatrix}
\]

(3)

\[\theta_{\text{PLL}} = \int [w_b + (K_p + \frac{K_i}{p})U_{\text{ref}}]dt\]  

(4)

Where \(K_p\) and \(K_i\) are the proportional and integral coefficients of the PI controller, respectively.

4. Submarine Cable and Grid-Connected System Model

The model of the transmitted submarine cable and grid-connected AC system is shown in Fig.4. Compared with conventional overhead lines, the submarine cable has a smaller capacitance to ground, which needs to be considered for building modeling for analyzing the harmonic. Therefore, the submarine cable uses a PI-type equivalent circuit. \(R_{H1}\) and \(L_{H1}\) are the equivalent resistance and inductance of the submarine cable, respectively. \(C_{11}\) and \(C_{12}\) are the capacitance to the ground of the submarine cable, respectively. \(R_s\) and \(L_s\) are the equivalent resistance and equivalent inductance of the grid-connected system, respectively.

5. Harmonic characteristic analysis

Based on the built PSCAD/EMTDC time-domain simulation model, the influence of factors such as the number of grid-connected wind turbines, the output of the wind turbines, the length of the AC submarine cable, and the strength of the grid-connected AC system on the harmonic characteristics are analyzed. The harmonic amplitude of the wind farm side and the harmonic amplitude of the grid-connected AC system side are calculated simultaneously, and the amplitude characteristics of the harmonics in two places are analyzed. On the basis, summarize the characteristics of harmonics and discuss the mechanism of harmonics generation.

5.1. Effect of the output of the wind turbine generators on the harmonic amplitude

When the wind farm output is gradually increased from 10% to 100%, combined with Fourier analysis, the amplitudes of the 5th, 7th, 11th, and 13th harmonics are calculated by simulation as shown in Figure 5 below.
For the 5th harmonic, when WTG output is 50% - 60%, the amplitude of the harmonic is higher. For the 7th harmonic, when WTG output is 30%, 70%, and 80%, the amplitude of the harmonic is higher. For the 11th harmonic, the amplitude is higher when the WTG output is 60%. For the 13th harmonic, the amplitude of the harmonic is higher when the WTG output is 10%, 30% and 60%. It can be concluded, with the output change of the WTG, the amplitude of each harmonic does not have obvious monotonic regularity. Further explanation of the complex mechanism is needed.

Figure 5 The amplitude of each harmonic current for different output of wind turbine generators

5.2. Effect of the number of WTG on the amplitude of each harmonic current
In the case of different number of grid-connected wind turbines in the wind farm (represented by the ratio of the number of wind turbines / the total number of wind turbines in the paper), the calculation results of the amplitude of each harmonic current are shown in Figure 6.

As can be seen from the figure 6, with the increase of the number of grid-connected wind turbines, the amplitude of each harmonic has an increasing trend. But there are also counter-examples in individual operating conditions. The main reason is that from the perspective of the injection of harmonic sources, the number of wind turbines increases, and the number of harmonic voltage sources increases. According to the superposition theorem, the harmonic current component may increase. However, the wind turbine itself has impedance characteristics. With the change of the number of the wind turbines, the equivalent impedance for the whole system will change, the resonance characteristics will change. There will be a resonance phenomenon, which may cause the increase in the number of wind turbines and the increase in harmonic currents not to show a linear correspondence.

5.3. Influence of short-circuit capacity
The output of the wind turbine is 30% of the rated output. The short-circuit capacity at the grid-point is gradually reduced from 7000MVA to 1204MVA. The voltage and current harmonics at the grid-point are calculated. The calculation results are shown in Figure 7 below.
As can be seen from the figure, for the 11th current harmonics, under the conditions of working conditions 3(2400MVA) and 4(1800MVA), the harmonics are the largest and exceed the standard. For the 13th harmonic, the maximum value of the harmonic appears in working condition 2(3600MVA). That is, for a certain number of grid-connected WTGs, when the harmonic amplitude is highest the system strength may not be the weakest. There is a certain "proportion relationship" between the system strength and the system's harmonic risk.

5.4. Comparative analysis of harmonic amplitudes between offshore stations and onshore stations
For the different output of the wind turbine, the harmonic current amplitudes of the onshore station and the offshore station are calculated respectively. Combined with Fourier analysis, the calculation results are shown in Figure 8 below. As can be seen from the figure, for each order of harmonics, the harmonic amplitude of the offshore station exceeds the harmonic amplitude of the onshore station(grid point).
5.5. Impact of AC submarine cable length
The calculation results of the harmonic amplitude characteristics of the onshore stations under different lengths of AC submarine cables are shown in Figure 9 below.

As can be seen from the figure, with the increase of the length of the AC submarine cable, when the length reaches 20km, the amplitude of the 13th harmonic in each harmonic is significantly higher than the rest of the harmonic components, indicating that the resonance frequency of the system is at the 13th harmonic. When the length of the submarine cable is further increased to 30km, the amplitude of the 11th harmonic increases significantly, which is much higher than the other harmonics in the system, indicating that the system's resonance frequency at this time should be near the 11th harmonic. When the length of the submarine cable is 25km, the amplitudes of the 11th and 13th harmonics do not increase significantly, but they are still higher than the amplitudes of the lower harmonics, indicating that the resonance frequency points at this time are 11th and 13th. between. It can be known that with the increase of the length of the submarine cable, the resonance frequency point of the system is shifted from high frequency to low frequency.

6. Conclusion
Based on the PSCAD/EMTDC time-domain simulation model of the offshore wind farm sending system through the AC submarine cable network, the paper calculates the harmonic amplitude characteristics. The conclusions are as follows: 1) The effect of the WTG output on the harmonic amplitude of the system is complicated. 2) With the increase of the number of wind turbines connected to the grid, the amplitude of each harmonic will monotonically increase and there will be an extreme value. 3) Under the condition of a certain number of wind turbines, there is a certain relationship between the short-circuit capacity of the system and the number of wind turbines. Under this relationship, the amplitude of the harmonic reaches the maximum value. 4) As the length of the AC submarine cable increases, the resonance frequency point of the harmonic shifts to the lower order frequency, and the lower order harmonic is more prone to increase in the amplitude of the harmonic Big.

Acknowledgments
This work is partly supported by National Natural Science Foundation of China (51737007, 51925701) and UNSW-Tsinghua Collaborative Research Seed Grants.

References
[1] Liu H, Xie X, He J, et al. Subsynchronous interaction between direct-drive PMSG based wind farms and weak AC networks[J]. IEEE Transactions on Power Systems, 2017, 32(6): 4708-4720.
[2] Du W, Chen X, Wang H, et al. A method of open-loop modal analysis to examine the SSOs in a multi-machine power system with multiple variable-speed wind generators[J]. IEEE Transactions on Power Systems, 2018, 33(4): 4297-4307.

[3] Guest E, Jensen K H, Rasmussen T W. Mitigation of Harmonic Voltage Amplification in Offshore Wind Power Plants by Wind Turbines with Embedded Active Filters[J]. IEEE Transactions on Sustainable Energy, 2019.

[4] Wang X, Blaabjerg F. Harmonic Stability in Power Electronic-Based Power Systems: Concept, Modeling, and Analysis[J]. IEEE Transactions on Smart Grid, 2018, 10(3): 2858-2870.

[5] Miao Z. Impedance-model-based SSR analysis for type 3 wind generator and series-compensated network[J]. IEEE Transactions on Energy Conversion, 2012, 27(4): 984-991.

[6] Harnefors L, Wang X, Yepes A G, et al. Passivity-based stability assessment of grid-connected VSCs—An overview[J]. IEEE Journal of emerging and selected topics in Power Electronics, 2015, 4(1): 116-125.

[7] Chen Z, Luo A, Huang X, et al. Relative Stability Assessment for Wideband Harmonic Resonances in Distributed Generation Power Plants[C]. conference of the industrial electronics society, 2019: 3417-3422.

[8] Zhang Y, Klabunde C, Wolter M. Harmonic Resonance Analysis for DFIG-based Offshore Wind Farm with VSC-HVDC Connection[C]//2019 IEEE Milan PowerTech. IEEE, 2019: 1-6.

[9] Harnefors L, Finger R, Wang X, et al. VSC input-admittance modeling and analysis above the nyquist frequency for passivity-based stability assessment[J]. IEEE Transactions on Industrial Electronics, 2017, 64(8): 6362-6371.

[10] Schwanz D, Bollen M, Larsson A. Some methods for harmonic emission determination in wind power plants[C]//2018 18th International Conference on Harmonics and Quality of Power (ICHQP). IEEE, 2018: 1-6.

[11] Bi T, Li J, Zhang P, et al. Study on response characteristics of grid-side converter controller of PMSG to sub-synchronous frequency component[J]. Iet Renewable Power Generation, 2017, 11(7): 966-972.

[12] Zhao M, Yuan X, Hu J, et al. Voltage dynamics of current control time-scale in a VSC-connected weak grid[J]. IEEE Transactions on Power Systems, 2015, 31(4): 2925-2937.

[13] Y. Li, L. Fan and Z. Miao, Stability Control for Wind in Weak Grids, in IEEE Transactions on Sustainable Energy, vol. 10, no. 4, pp. 2094-2103, Oct. 2019.

[14] Xu Y, Cao Y. Sub-Synchronous Oscillation in PMSGs-based Wind Farms caused by Amplification Effect of GSC controller and PLL to Harmonics[J]. Iet Renewable Power Generation, 2018, 12(7): 844-850.

[15] Glasdam J B, Bak C L, Kocewiak L H, et al. Detailed Equivalent VSC-HVDC Modelling for Time Domain Harmonic Stability Studies in Wind Power Plants[J]. Energies, 2019.

[16] Vieto I, Sun J. Real-time simulation of subsynchronous resonance in Type-III wind turbines[C]. 2014 IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL), Santander, Spain, 2014: 1-8.

[17] Karaagac U, Faried S O, Mahseredjian J, et al. Coordinated control of wind energy conversion systems for mitigating subsynchronous interaction in DFIG-based wind farms[J]. IEEE Transactions on Smart Grid, 2014, 5(5): 2440-2449.