Modelling and resonance analysis of wind power integration via flexible HVDC considering wind speed and wind farm location

Xiaobao Hu1,2, Xiao Wang1,3, Hui Liu1,3, Linlin Wu1,3, Lele Niu1,2 and Siqing Sheng2

1 State Grid Jibei Electric Power Co. Ltd. Research Institute, North China Electric Power Research Institute Co. Ltd., Beijing, China
2 Department of Electrical and Electronic Engineering, North China Electric Power University, Baoding, China
3 Grid-connected Operation Technology for Wind-Solar-Storage Hybrid System State Grid Corporation Key Laboratory, Beijing, China

E-mail: 1465951274@qq.com

Abstract. Field experience has shown that harmonic resonance may occur in wind farms integration through a flexible HVDC transmission system. The impact on resonance characteristics from wind speed and length of the connection line from wind farm to flexible HVDC converter station is studied in this paper. First, the system model of wind farm integration through flexible HVDC system is established, including the whole structure of electrical model, control structures of converters and the impedance measurement model. Then, the effect of the line length and wind speed on the impedance characteristics of interconnected system is analyzed, and the aggregated RLC circuit approach is used to evaluate the risk of potential resonance quantitatively. Finally, the simulation results on the RT-LAB platform validate the theoretical analysis.

1. Introduction

The application and development of flexible HVDC technology provide a good implementation scheme for long distance transportation of large-scale wind power. However, resonance or instability phenomena might occur in the wind power integration through flexible dc system [1-3].

At present, the complicated resonance mechanism caused by the interaction of multiple power electronic equipment in the system of wind farms integration via flexible HVDC transmission system is a research hot spot. The effect of control parameters of flexible HVDC control loop, wind turbine converter current loop and phase lock loop (PLL) on the system stability was studied [4], where it is pointed that accelerating the control speed of flexible HVDC or slowing down the control speed of the PLL can improve the system stability. It was further proposed that system resonance is aroused when the control bandwidth of VSC-HVDC converter is less than the wind turbine converter [5]. Moreover, the stability margin of the interconnection system is influenced by circulation control of flexible HVDC consisting of modular multilevel converter [6]. However, there is little research on the comprehensive influence of connected line length and wind speed on the stability of HVDC-connected wind farms.

It is studied that the impact of wind speed and location on the resonance risk of wind farm integration through flexible HVDC system in this paper. First, the system model of doubly-fed induction generator
and two-terminal MMC-HVDC is built, and the control circuit and impedance measurement model are described in detail. Then, the change of the impedance characteristics of interconnected systems under the condition of different line lengths and wind speed is analyzed. Further, the variation trend of system resonance frequency is analyzed and the resonance parameter based on the aggregated RLC fitting method is introduced to evaluate potential resonance risk. Finally, the same simulation model is built on the RT-LAB platform and the simulation results validate the theoretical analysis.

2. Interconnection system model

2.1. Overall Configuration of interconnection system

The typical topology of wind power integration via flexible HVDC is shown in figure 1. The flexible dc transmission system is two-terminal MMC-HVDC structure, including MMC converter, converter transformer and dc line. Wind farm is made up of doubly-fed induction generators and box-type transformers, which can be modelled by single machine polymerization. The wind farm connect to Point of Common Coupling (PCC) by step-up transformer and ac line. The terminal ac power grid can be realized by using Thevenin equivalent modelling.

![Figure 1 Topology structure of wind farms integration via an MMC-based HVDC system](image)

2.2. MMC converter station control

Under normal operating conditions, the MMC1 is responsible for controlling the amplitude and frequency of the ac voltage at PCC, providing a stable ac power source for the wind farm. The MMC2 is responsible for controlling the voltage stability of the dc bus and providing certain reactive power to the ac grid. The specific double loop control of MMC1 is shown in figure 2. The control outer loop gets current reference value based on ac voltage and frequency information. The control inner loop gets the converter output voltage reference through closed-loop control of valve side current, according to reference value of the current and angle. Main controller of inner and outer loop adopts the dq decoupling method, including the outer loop control based on Proportional Integral (PI) block and the inner current control based on PI and coupling units.

![Figure 2 The control structure of mmc deliver converter](image)

2.3. Wind farm converter control

The wind farm is equivalent to a doubly-fed induction generator, and the control structure of grid side converter (GSC) is shown in figure 3. The inverter keeps the dc bus voltage of back-to-back full power converter constant by controlling the outer voltage loop in the control loop, the reference current value
is given by the outer dc voltage control. The coordinate transformation angle $\theta_{PLL}$ of dq axis coordinate system is obtained through the phase locked loop, providing coordinate transformation benchmark for the system. The basic structure of phase locked loop is shown in figure 4.

2.4. Impedance measurement model

Assuming that the MMC2 can keep dc voltage constant at steady state, at this point, the influence of MMC2 on MMC1 can be ignored. So to simplify the analysis, a dc voltage source can be used instead of the MMC2 to simulate the effect of the dc-side voltage. In addition, the wind farm side converter (WSC) is decoupled from GSC through the dc side capacitance, so the interaction between WSC and MMC-HVDC system is negligible. In order to simplify system analysis, wind turbine, generator and WSC are equivalent to a current source. Therefore, the simplified equivalent circuit impedance model of the interconnected system is shown in figure 5. Taking PCC as a demarcation point, the interconnection system shown in Figure 1 can be divided into the wind turbine subsystem and the flexible dc subsystem. The equivalent sequence impedance model is shown in Figure 5. The flexible dc subsystem is equivalent to voltage source $U_M$, impedance of converter station $Z_{MMC}$ and impedance of converter transformer $Z_T$. The wind turbine subsystem is equivalent to current source $I_W$, impedance of wind turbine $Z_{wind}$ and impedance of collection line $Z_{grid}$.

3. Analysis of the influence on the length of line

3.1. Impedance characteristics analyses

The impedance characteristics of interconnected system can be obtained and displayed as impedance-versus-frequency curves. The interconnection system model shown in Fig 1 is built, whose parameters are shown in Table 1. The different lengths of line between HVDC converter station and wind farm may have impact on the resonance characteristics of interconnected system. With the rated wind turbine output, we change the length of the line gradually and observe its effect on the impedance characteristics of system. The equivalent impedance characteristics of interconnected systems with different line lengths in the range of 250Hz to 450Hz is shown in figure 6. The equivalent impedance of the interconnected system is $Z_S$, and the equivalent resistance of the interconnected system is $R_S$. 

---

**Figure 3.** The control structure of grid side converter.  
**Figure 4.** The basic structure of a phase-locked loop.  
**Figure 5** Impedance model of interconnected system.
The variation of line length can change the impedance characteristics of the system. If the line length increased to 18 km, the interconnected system becomes negative damping resonance condition at 367.3Hz, according to the equivalent circuit damping stability criterion [7]. With the length of line further increased, the resonance frequency continues to decrease.

3.2. Oscillation risk evaluation

The method in literature [8] is used to evaluate the resonance risk of the system quantitatively. With the rated wind turbine output, we change the length of the line gradually and observe its effect on the characteristics of resonance and evaluate the resonance risk. Table 2 shows the RLC second-order circuit parameters of the fitted impedance frequency curve when the length of the line changes.

As shown in table 2, if line length is increased to 18 km, the interconnected system began to oscillate. With the line length further increased, the resonance frequency continues to decrease, then the resonance risk increases.

4. Analysis of the influence on the wind speed

4.1. Impedance characteristics analyses
With the length of the line set to 15 km, we change the wind speed gradually and observe its effect on impedance characteristics of system. The impedance characteristics of interconnected systems with different wind speed in the range of 250 to 450Hz is shown in figure 7. The variation of wind speed can change the impedance characteristics of the system. If the wind speed decreased to 0.75pu, the interconnected system becomes negative damping resonance condition around the resonance frequency. With the wind speed further decreased, the resonance frequency continues to decrease.

![Figure 7](image)

Figure 7 The impedance characteristics of system with different wind speed

4.2. Oscillation risk evaluation

4.2.1. Table 3 shows the RLC second-order circuit parameters of the fitted impedance frequency curve when the wind speed changes.

| Wind speed (pu) | R L C σ ω (Hz) |
|----------------|----------------|
| 0              | -15.7661 132.8537 5.56E-08 -0.0593 367.8053 |
| 0.5 pu         | -54.4586 145.0313 7.66E-08 -0.1877 299.9837 |

As shown in table 3, the stability of the system is different under different wind speed conditions. The higher the wind speed, the more stable the system is. With the wind speed decreased, the resonance frequency continues to decrease, then the resonance risk increases.

5. Simulation verification

The validity of theoretical analysis is proved by time domain simulation on RT-Lab. The waveforms of simulation adjusting the wind speed and the line length are shown in figure 8, which are consistent with impedance analysis and circuit fitting analysis.
Figure 8 (a) The current waveform and spectrum characteristic of phase a at the PCC point for the interconnection system with rated wind turbine output and 15 km line.

Figure 8 (b) The current waveform and spectrum characteristic of phase a at the PCC point for the interconnection system with rated wind turbine output and 18 km line.

Figure 8 (c) The current waveform and spectrum characteristic of phase a at the PCC point for the interconnection system with 0.75 rated wind turbine output and 15 km line.

The system is stable with the rated wind turbine output and 15 km line as shown in Figure 8 (a). The resonance phenomenon occurs with the length of line increased to 18 km, and the current of phase a through the interconnection system PCC point contains 2.3% of the 368Hz harmonic components, as shown in Figure 8 (b). Under the condition of interconnection system with 0.75 rated wind turbine output and 15 km line as shown in Figure 8 (c), the current of phase a through PCC point contains 1.8% of the 368Hz harmonic components.

6. Conclusion
As the research background based on doubly-fed induction generators integration via a two-terminal MMC-HVDC system, the influence of wind speed and connected line length on the resonance risk is studied. By the impedance analysis and time domain simulation, the resonance frequency decreases with the line length increased, while the resonance damping becomes small. In the case of fixed wind farm location, the less wind turbines power is, the less stability margin of the system is. Therefore, the wind farm should control whether integrate wind turbines to grid according to the real-time wind speed.
Acknowledgments
This paper is partly supported by the national R&D project (A comprehensive demonstration project for smart grid supporting low-carbon winter Olympics, 2016YFB0900500) and State Grid Corporation of China Headquarter technology project (52010118000L).

References
[1] Fan Xinming, Guan Lin, Xia Chengjun, et al. 2013 Multilevel VSC-HVDC Applied in Wind Power Integration J High Voltage Engineering 39(2):497–504
[2] Zhao Y，Zheng B，He Z. 2012 The Control Mode and Operating Performance of Nanhu H VSC-HVDC Demonstration Project J Southern Power System Technology (6): 6–10
[3] Buchhagen C，Rauscher C，Menze A，et al. 2015 BorWin1 - First Experiences with harmonic interactions in converter dominated grids C International ETG Congress; 2016 Die Energiewende - Blueprints for the new energy age Proceedings of VDE pp 1–7
[4] Liu H，Sun J. 2014 Voltage Stability and Control of Offshore Wind Farms With AC Collection and HVDC Transmission J IEEE Journal of Emerging & Selected Topics in Power Electronics 2(4): 1181–89
[5] Amin M，Molinas M. 2017 Understanding the Origin of Oscillatory Phenomena Observed between Wind Farms and HVDC Systems J IEEE Journal of Emerging & Selected Topics in Power Electronics 5(1): 378–392
[6] Lyu J，Cai X，Molinas M. 2016 Frequency Domain Stability Analysis of MMC-Based HVdc for Wind Farm Integration J IEEE Journal of Emerging & Selected Topics in Power Electronics 4(1): 141–151
[7] WANG Xiao，LIU Hui，HU Xiao-bao，et al.2018 Analysis of Risk and Impacting Factors of Oscillation in Wind Farms Integration via a Flexible HVDC System Based on Equivalent Circuit Damping Stability Criterion J Global Energy Interconnection (1):48–55
[8] Liu Huakun，Xie Xiaorong，Zhang Chuanyu，et al. 2017 Quantitative SSR analysis of series-compensated DFIG-based wind farms using aggregated RLC circuit model J IEEE Transactions on Power Systems 32(1): 474–483