Impact of Wind Generators Number and Location on the Resonance Risk of Wind Farm Integration through Flexible HVDC System

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Abstract. Resonances or instability phenomena may occur in wind farms integration through a flexible HVDC transmission system. The relationship between the resonance risk and wind turbines number under different lengths of the line from wind farms to the flexible HVDC converter station is studied in this paper. First, the effect of the line length on the impedance characteristics of interconnected system is analyzed, and the aggregated RLC circuit approach is applied for the quantitative assessment of potential resonance risk. Then, the variation trend of system impedance characteristics caused by different wind turbines number is revealed, and resonance risk affected by the number of wind turbines integrated from the different location is evaluated by calculating system resonance damping around the resonant frequency. Finally, the simulation results on the RT-LAB platform validate the theoretical analysis.

1. Introduction
In recent years, the renewable energy represented by wind power has been developed rapidly, and the regional power system with a high proportion of renewable energy is gradually formed. However, the renewable energy generators are connected to the power grid directly or indirectly by the power electronic converter, while the interaction between converters and power grid may cause resonances or instability problems. The interaction between the wind turbines and the series-compensated system caused sub-synchronous resonances of 3–10Hz in the Hebei Guyuan district of China in 2011. The sub-synchronous resonances of 20–40Hz involving wind turbines occurred in Xinjiang Hami district of China in 2015. The resonance phenomena at hundreds of Hertz appeared in the German North Sea wind farms connected to the onshore ac grid through flexible HVDC transmission system, when the filter capacitors of converter station was damaged in 2014.

Many scholars have conducted extensive research on the resonance mechanism caused by the interaction between wind farms and weak ac power grid or series-compensated system. The reason for the resonance of wind farms connected by weak ac system is wind turbines behave as a “capacitive reactance with a negative resistance” at the resonant frequency, whose interaction with the AC grid (considered as inductance) constitutes the L-C-R resonance circuit and negative resistance effect will lead to risky resonance phenomenon [1]-[3]. Similarly, the resonance phenomenon of the doubly-fed wind power plants connected by series-compensated lines is induced by negative damping.
characteristics, which is an induction generator effect involving the controller of wind turbine [4], [5]. Literatures [1], [6]-[7] established the model of type-III and type-IV wind turbines respectively connected to the ac power grid, and pointed out that the weaker the strength of ac system (the longer the connection line), the more unstable the system is. Further, the influence of the grid-connected wind turbines number on the system stability was studied in [4]-[5], [8]-[9], and it was pointed out that the risk of system resonance increases with the increase of the wind turbines number.

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. Literature [10] reported a sub-synchronous oscillation phenomenon of doubly-fed induction generator (DFIG) integration via an MMC-based HVDC system, analyzed the distribution and transmission mechanism of subsynchronous oscillation current in HVDC system. 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 in [11], 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 [12]. Moreover, the stability margin of the interconnection system is influenced by circulation control of flexible HVDC consisting of modular multilevel converter [13]. However, there is little research on the comprehensive influence of connected line length and integrated wind turbines number on the stability of HVDC-connected wind farms.

It is studied that the impact of wind generators number and location on the resonance risk of wind farm integration through flexible HVDC system in this paper. First, the system model consisting of doubly-fed induction generators integration via two-terminal MMC-HVDC is built. Using the equivalent circuit damping stability criterion, the change of the impedance characteristics of interconnected systems under the condition of different line lengths is analyzed. Further, the potential resonance risk is evaluated by introducing resonance damping parameter based on the aggregated RLC fitting method. Taking the wind turbines number and location into account, the equivalent RLC circuit parameters under a variety of conditions are calculated, then the variation trend system resonance frequency is analyzed and the resonances risk is evaluated quantitatively. Finally, the same simulation model is built on the RT-LAB platform and the simulation results validate the theoretical analysis.

2. Interconnection system model
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)

3. Influence analysis on the length of line

3.1. Impedance characteristics analyses
Taking PCC as a demarcation point, the interconnection system can be divided into the wind turbine subsystem and MMC-HVDC subsystem. Impedance analysis is used to analysis the impedance
characteristics of interconnected systems. The different lengths of line may have impact on the impedance characteristics of interconnected system. With the number of wind turbines set to 700, 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 in the range of 250 to 450Hz is shown in figure 2. The dashed line indicates the equivalent impedance amplitude of the MMC-HVDC subsystem $|Z_W|$, and the dash-dotted line indicates the equivalent impedance amplitude of the wind turbine subsystem $|Z_M|$, the solid line represents the equivalent resistance of the interconnection system $R_z$. According to the equivalent circuit damping stability criterion [14], the equivalent resistance $R_z$ of the interconnection system is negative at two resonance points, at this point, the system is in an unstable state.

![Figure 2. The impedance characteristics of system with different line lengths](image)

As shown in figure 2, the variation of line length can change the impedance characteristics of the system, and the interconnected system become negative damping resonance condition when the length increased to 18 km. With the length of line further increased, the resonance frequency continues to decrease.

3.2. Resonance risk evaluation

In order to evaluate the resonance risk of the system quantitatively, the method in literature [9] is used. According to literature [9], impedance-versus-frequency curves can be approximated with a second-order series RLC circuit model in a very small frequency range. The characteristics of resonance can be effectively determined by the circuit parameters, i.e. $R$, $L$ and $C$. The damping $\sigma$ and resonance frequency $\omega$ of the circuit, or of the resonance, can be computed by:

$$\sigma = \frac{R}{2L} \quad \omega = \left(\frac{1}{LC} - \frac{R}{2L}\right)^{1/2}$$

Obviously, if $R > 0$, $\sigma$ is positive, indicating the system has positive damping and resonance is stabilized; otherwise, unstable resonance will occur.

With the wind turbines number set to 700, we change the length of the line gradually and observe its effect on the characteristics of resonance and evaluate the resonance risk. Table1 shows the RLC second-order circuit parameters of the fitted impedance frequency curve when the length of the line changes.

As shown in table 1, 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.
Table 1 Parameters of the aggregated RLC circuit model and resonance

| Length of line | R   | L       | C       | σ        | ω       |
|---------------|-----|---------|---------|----------|---------|
| 15            | +   | NaN     | NaN     | NaN      | NaN     |
| 16            | +   | NaN     | NaN     | NaN      | NaN     |
| 17            | +   | NaN     | NaN     | NaN      | NaN     |
| 18            | -11.1059 | 67.2727 | 1.09E-07 | -0.0825 | 368.4791 |
| 19            | -17.5231 | 39.1840 | 1.78E-07 | -0.2236 | 360.5519 |
| 20            | -29.3844 | 43.0225 | 2.06E-07 | -0.3415 | 351.5429 |

4. Influence analysis on the number of wind turbines

4.1. Impedance characteristics analyses

With the length of the line set to 18 km, we change the wind turbines number gradually and observe its effect on impedance characteristics of system. The impedance characteristics of interconnected systems with different wind turbines number in the range of 250 to 450Hz is shown in figure 3. The variation of wind turbines number can change the impedance characteristics of the system. If the line length is 18 km and wind turbines number increased to 700, the interconnected system becomes negative damping resonance condition around the resonance frequency. With the wind turbines number further increased, the resonance frequency continues to decrease.

![Figure 3](image-url)

Figure 3 The impedance characteristics of system with different wind turbines number

4.2. Comprehensive resonance risk evaluation considering location factors

To evaluate the influence of wind turbines number and line length on the resonance risk of interconnected system, aggregated RLC circuit parameters are fitted by the impedance frequency curve of the system under different wind turbines number and line length. The resonance frequency \( \omega \) and resonance damping \( \sigma \) are shown in table 2 and table 3.

As shown in table 2 and table 3, resonance phenomenon will occur when wind turbine number or line length is increased and the resonance frequency is near 350Hz in unstable region. In the stable area with fewer wind turbines number and shorter line length, there is no such resonance mode in the interconnection system. In the resonance region, the resonant frequency and the resonant damping decrease with the increase of wind turbine number and the line length. The influence trend of wind turbines number and line length on system resonance risk is shown in figure 4, which are positively correlated.

![Figure 4](image-url)
Table 2 The resonance frequency $\omega$ with different wind turbines number and line lengths

| Wind turbines number | Length of line (Km) |
|----------------------|---------------------|
| 15                   | 16                  | 17     | 18      | 19      | 20      |
| 500                  | NaN                 | NaN    | NaN     | NaN     | NaN     |
| 600                  | NaN                 | NaN    | NaN     | NaN     | 371.3421|
| 650                  | NaN                 | NaN    | NaN     | 370.9327| 360.0527|
| 700                  | NaN                 | NaN    | 368.44  | 360.5519| 351.5249|
| 730                  | NaN                 | 364.8341| 360.3511| 356.6492| 348.4553|
| 760                  | 365.003             | 361.1206| 351.3871| 351.3871| 345.096 |
| 800                  | 358.5092            | 353.6716| 346.4375| 346.6751| 338.4791|
| 900                  | 341.3561            | 336.9012| 334.6977| 331.9766| 327.1952|

Table 3 The resonance damping $\sigma$ with different wind turbines number and line length

| Wind turbines number | Length of line (Km) |
|----------------------|---------------------|
| 15                   | 16                  | 17     | 18      | 19      | 20      |
| 500                  | NaN                 | NaN    | NaN     | NaN     | NaN     |
| 600                  | NaN                 | NaN    | NaN     | NaN     | -0.104  |
| 650                  | NaN                 | NaN    | NaN     | -0.1526 | -0.2374 |
| 700                  | NaN                 | NaN    | -0.0825 | -0.2236 | -0.3415 |
| 730                  | NaN                 | -0.1025 | -0.2051 | -0.363  | -0.5753 |
| 760                  | -0.1349             | -0.214  | -0.3165 | -0.5207 | -0.693  |
| 800                  | -0.126              | -0.2579 | -0.328  | -0.583  | -0.7554 | -0.947  |
| 900                  | -0.2436             | -0.3947 | -0.5048 | -0.7139 | -0.8852 | -1.08   |

Figure 4 The influence trend of wind turbines number and line length on system resonance risk

5. Simulation verification
To verify the correctness of the above analysis, the interconnection system model shown in Fig 1 is built on the real-time simulation platform of RT-Lab, whose parameters refer to literature [14]. The waveforms of simulation adjusting the wind turbines number and the line length are shown in Figure 5, which are consistent with impedance analysis and circuit fitting analysis.

The system is stable with 700 DFIGs and 15 km line as shown in figure 5 (a). The resonance phenomenon occur 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 5 (b). On the basis of 18 km line, with wind turbines number increased to 900, the current of phase a through the interconnection system PCC point contains 2.8% of the 332Hz harmonic
components as shown in figure 5 (c), where the resonance is more serious and the resonance frequency is lower in contrast to figure 5 (b). Under the condition of interconnection system with 900 DFIGs and 20 km line as shown in figure 5 (d), the current of phase a through PCC point contains 3.2% of the 328Hz harmonic components, where resonance phenomenon is the most serious and the resonance frequency is lowest.

![Figure 5(a)](image1)

**Figure 5 (a)** The current waveform and spectrum characteristic of phase a at the PCC point for the interconnection system with 700 DFIGs and 15 km line.

![Figure 5(b)](image2)

**Figure 5 (b)** The current waveform and spectrum characteristic of phase a at the PCC point for the interconnection system with 700 DFIGs and 18 km line.

![Figure 5(c)](image3)

**Figure 5 (c)** The current waveform and spectrum characteristic of phase a at the PCC point for the interconnection system with 900 DFIGs and 18 km line.
ith the line length increased, while the resonance damping becomes small. In the converter station, the interconnection system.

The interconnection system is difficult to stably. Therefore, large wind farms with more wind turbines should be planned and constructed closer to the flexible HVDC converter station for the stability requirement of the interconnection system. The influence of wind speed and multiple wind farms on the resonance characteristics of the system will be considered more comprehensively in subsequent studies.

7. References

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Figure 5 (d) The current waveform and spectrum characteristic of phase a at the PCC point for the interconnection system with 900 DFIGs and 20 km line.

6. Conclusion

As the research background based on doubly-fed induction generators integration via a two-terminal MMC-HVDC system, the influence of wind turbines number 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 more wind turbines number is, the less stability margin of the system is. If the wind turbines are too many and far away from the HVDC converter station, the system is difficult to operate stably. Therefore, large wind farms with more wind turbines should be planned and constructed closer to the flexible HVDC converter station for the stability requirement of the interconnection system. The influence of wind speed and multiple wind farms on the resonance characteristics of the system will be considered more comprehensively in subsequent studies.
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