Research on the Impact on Sub-synchronous Resonance Risk from DFIG Number and Series-compensated Degree

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Abstract. Sub-synchronous resonance (SSR) occurred in the power system with both Doubly Fed Induction Generators (DFIGs) and series-compensated lines. Existing paper discovered the nonlinear relationship of SSR damping and the number of DFIGs. In this paper, the equivalent model of wind farms and series-compensated power system in Guyuan is built in RT-LAB. Based on that model, the SSR characteristics of wind farms in Guyuan area under different DFIG numbers and line parameters are investigated through impedance method. The results show that: 1) The relationship between SSR characteristics and DFIG number is nonlinear in Guyuan area. Under the condition of a given wind speed, there is certain number of DFIGs which will induce worst damping effect. 2) A higher series-compensated degree results in a less stable system.

1. Introduction

Wind energy has been widely used and developed worldwide as a clean and environmentally friendly renewable energy source in recent years. China has now become the country with the largest installed capacity of wind power in the world. However, wind power is mainly concentrated in remote areas and is far from the center load. Therefore, the long-distance large-scale delivery of wind power is imperative. Series-compensated technology is often used to increase the transmission capacity and perform long-distance power transmission, but it also leads to SSR problems. There have been many subsynchronous resonance accidents caused by series-compensated at home and abroad.

For the SSR problem of DFIG-series compensated system, the existing research methods mainly include eigenvalue method and impedance analysis method, and verified by time-domain simulation. The eigenvalue method linearizes the DFIG and the series-compensated transmission system models respectively, and calculates the eigenvalues of the system's linearization matrix to obtain the oscillation modes of the system. The Nyquist curve or Bode plot is used for impedance analysis method to determine the stability by establishing the system's small signal impedance model. Using the above two methods, some achievements have been made in mechanism research and SSR control. In [7-8], it showed that the induction generator effect is the main reason for the SSR.
In [11-17], it studied the influence of wind speed, series-compensated degree and DFIG control parameters on the SSR characteristics of the system, and pointed out that: the lower the wind speed, the greater the series-compensated degree and the RSC (Rotor-side converter, RSC) current control proportional coefficient, the higher the SSR risk. At present, most of the studies have been considered by a single DFIG through the series-compensated line to send out the system, and few literatures study the relationship between the system's SSR characteristics and the number of DFIG. In [18], it was found that the SSR characteristics of the DFIG-series compensated system were nonlinearly related to the number of DFIGs, and the line parameters were not considered which has effect on the SSR risk of Guyuan area.

In order to furtherly study the nonlinear relationship between SSR characteristics and the number of DFIG in the Guyuan area, this paper first establishes a model of DFIG-series compensated transmission system in the Guyuan area. Based on this model, a small signal impedance model of the system is established. Using impedance analysis method, the conditions for system stability should be analyzed. Based on this, the relationship between the SSR characteristics of the Guyuan area and the number of DFIG is studied.

2. DFIG-series-compensated system modelling and analysis

2.1 DFIG-series-compensated system modelling

This paper takes the equivalent modeling of a certain wind farm in North China. The wind farm is boosted by the transformer and then connected to the series-compensated transmission system, taking account of the impedance of the low-voltage transmission line, from the perspective of the wind farm, the equivalent series compensation degree of the grid is 6.67% [1-3]. When the operating conditions of each wind turbine in the wind farm are not much different, the entire wind farm can be equivalent to a DFIG [12-13]. The equivalent system is shown in figure.1.

![Figure 1. The equivalent model of wind farm series-compensated system](image1)

![Figure 2. Small-signal model of DFIG and series-compensated transmission system](image2)

2.2 DFIG-series-compensated system analysis

In this paper, impedance analysis method is used to analyse the characteristics of SSR in Guyuan area. Impedance analysis is based on the system's small signal impedance model and uses Nyquist curves or Bode plots to determine the system stability. The small-signal impedance model of the DFIG-series compensated transmission system shown in figure.1 is shown in figure.2.

[7] pointed out that the stability of the system is determined by the impedance of the grid and the impedance of the DFIG. The stability of the system can be analyzed by the Bode plot of the DFIG impedance $Z_{DFIG}(s)$ and the grid impedance $Z_{Grid}(s)$. The frequency corresponding to the intersection point of DFIG impedance and grid impedance amplitude in Bode plot is the SSR frequency. The phase angle margin of the system can be judged by using the phase characteristics of the DFIG impedance and the grid impedance at the SSR frequency. If the phase angle margin at the intersection is less than 0, then the system impedance appears in the form of negative resistance + reactance, the system is unstable, and there is SSR risk; on the contrary, if the phase angle margin is greater than 0, then the system impedance shows the form of positive resistance + reactance. At this time, the system is stable and there is no SSR risk.
3. The relationship analysis between SSR risk and DFIG number

3.1. SSR simulation of DFIG-series-compensated system
In this paper, the DFIG-series-compensated system equivalent model of the Guyuan area is shown in figure 1, which is constructed on the RT-LAB for simulation. In [18], it pointed out that multiple small-capacity DFIGs can be equivalent to a single large-capacity DFIG, and all DFIG capacity is considered equal.

When the wind speed is 5m/s, 10 DFIGs, 100 DFIGs, and 1000 DFIGs are simulated by an equivalent grid transmission system. The DFIG stator current waveform is shown in figure 3.

Figure 3 shows that the system is stable when 10 DFIGs are sent through equivalent series-compensated lines; the system is resonant when 100 DFIGs and the system is stable when 1000 DFIGs. It can be inferred that with the increase of the number of DFIGs, the system has a process from stability to instability and then return to stability. The system SSR characteristics are nonlinear with the number of DFIGs.

![Figure 3. The line current with equivalent series-compensated line and different DFIG number](image)

3.2. The relationship analysis between SSR characteristics and DFIG number
Using the frequency scan method [9], the impedance characteristics of the wind farm are every 1 Hz in the frequency range of 1-100 Hz when the wind speed is 5 m/s. The Bode plots of equivalent grid impedance and different fan impedances are shown in figure 4.

From figure 4, it can be seen that the impedance amplitude curves of 10, 100, and 1000 DFIGs all intersect with the impedance amplitude curve of the equivalent network, and the frequency at the intersection is 1.8 Hz, 4.5 Hz, and 9.6 Hz, respectively. In the case of 10 wind turbines connected to the grid, the system phase angle margin corresponding to the frequency at the intersection point is 43.5°, and no resonance occurs in the system. In the case of 100 wind turbines, the phase angle margin at the intersection is -4.7°, and resonance will occur in the system. In the case of 1000 wind turbines, the phase margin at the intersection is 9.3°, and no resonance occurs in the system.

From the above analysis, it can be seen that with the increase of the number of DFIGs, the system SSR characteristics have a process of deterioration and improvement. The system must also have a process from stability to instability and then return to stability. The relationship between the system phase margin and the number of DFIGs in the Guyuan area wind farm at a wind speed of 5m/s is shown in figure 5.

![Figure 4. The Bode plots of equivalent grid impedance and different fan impedances](image)

![Figure 5. The relationship between the system phase margin and the number of DFIGs](image)
In order to further study the relationship between the SSR characteristics and the number of wind turbines in the Guyuan area, change the wind speed of the wind farm, the relationship between the system phase margin and the number of wind turbines at different wind speed in the Guyuan area is shown in figure 6.

Figure 6. Phase margins change with DFIG number and wind speed

Figure 7. Bode plot of different numbers of DFIG and different series-compensated lines

Similarly, with the series-compensated degree increases, the capacitance of the line is enhanced within 2-10 Hz, and the phase curve of the line moves downwards, so that the corresponding phase
angle margin at the intersection point of the amplitude also decreases, which deteriorates the system's SSR characteristics and increases the SSR risk.

Figure 8 shows the relationship between DFIG number and the phase margin under different series-compensated degree. With the system series-compensated degree gradually decreases, the phase margin gradually increases, the system SSR characteristics gradually improve, and the system becomes more stable.

![Figure 8. Phase margins change with DFIG number and compensation level](image)

5. Conclusion
This paper first establishes the equivalent power transmission model in Guyuan area. Based on this model, the impedance analysis method is used to study the relationship between SSR characteristics of wind power-series compensation system and the number of DFIGs and line parameters in the Guyuan area. The main conclusions of the paper are as follows:

1) Using impedance analysis method, it is revealed from the impedance level that the SSR characteristics of the DFIG-series compensated transmission system in the Guyuan area are nonlinear with the number of DFIGs. At different wind speed, there is the number of DFIG with the worst damping characteristics of the system.

2) For a certain number of DFIGs, the SSR risk of the system series is reduced with lower series-compensated degree.

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