Impedance characteristics of DFIGs considering the impacts of DFIG numbers and its application on SSR analysis

J J You¹, W Y Ning², H Jiang², Y X Dong¹, H Liu² and Y Li²
¹ North China Electric Power University, Changping District, Beijing 102206, China
² State Grid Jibei Electric Power Research Institute, Xicheng District, Beijing 100045, China

Abstract. Sub-synchronous resonance (SSR) occurred in the power system with both Doubly Fed Induction Generators (DFIGs) and series-compensated lines. There have been several papers focusing on the analysis of such SSR phenomenon. To the authors’ knowledge, the impacts of DFIG numbers are seldom considered in existing papers. In this paper, the impedance characteristics of DFIGs under different numbers are analyzed. Then the relationship between DFIG numbers and SSR characteristics is discussed. The contributions to be included in the paper are as following: 1) the impedance of N DFIGs is roughly equal to 1/N of the impedance of one DFIG. 2) The SSR risk of system is related with both the numbers of DFIGs and the parameters of the series-compensated lines.

1. Introduction

Wind power is developing all over the world. However, most of the wind farms are far away from the load center, which always need long-distance transmission. The series-compensated technology is widely used in long-distance transmission as it can improve the capacity of the transmission line. The wind power of wind farms are usually transmitted via series compensated lines. However, this technology will also bring the risk of SSR [1-3].

In recent years, many SSR accidents occurred in power systems with DFIG and series-compensated lines. For example, in the wind farms of USA (Electric Reliability Council of Texas and Xcel Energy) and China (Guyuan, Hebei Province) [4]. The issue has aroused great concern from academic and industrial communities as it would seriously weaken the safe and reliable operation of the wind farms as well as the whole power system.

Previously, theoretical research and simulation studies have been conducted to investigate the mechanism and characteristics of this SSR phenomenon [5-12]. In [13], the author focused on the frequency scan method for SSR study. Reference [5] first analyzed the impedance of the grid and the DFIG and then analyze the stability of the whole system using the Nyquist stability criterion. Similar model-based simulation and eigenvalue-based analysis for a DFIG with radial connected compensated line can be found in [14] and [15]. The authors used frequency scan method to formulate the small-signal impedance model of the DFIG in [16]. In addition, the factors which effect the stability of the series-compensated two-WTG system are examined in [17].

Existing studies have only focused on the wind farm with a single DFIG. As a consequence, the impacts of DFIG numbers are seldom considered. To address this issue, the impedance characteristics of DFIGs with different numbers are analyzed in this paper. The contributions to be included in the
paper are in the following aspects:

1) The impedance characteristics of different numbers of DFIGs are studied.

2) The SSR characteristics of series-compensated transmission system under different numbers are studied. Moreover, the influence of the two parameters of series-compensated lines on the SSR characteristics of the system is compared.

The rest of the paper is as follows. Section II introduces the series-compensated transmission system modeling and basics of frequency scan techniques for measuring the impedance of DFIG. Section III analyzes the impedance characteristics of DFIG under different numbers and parameters of series-compensated lines. Section V concludes the whole paper.

2. Modeling of series-compensated transmission system and basics of the frequency scan method
The series-compensated transmission system model is established for large wind farms first. Then the small-signal model of DFIG and series-compensated transmission system is built on the basis of series-compensated transmission system model. The system stability criterion can be derived from the small-signal model of DFIG and series-compensated transmission system. Finally the basics of frequency scan techniques which are widely used for measuring the impedance of DFIG are introduced.

2.1. Modeling of series-compensated transmission system with a number of DFIGs
For large wind farms, it can be considered as multiple identical wind farms connected to a common collecting bus. The series-compensated transmission system with a number of DFIGs is built in Figure 1. Where $R_g$ is the resistance of transmission lines, $L_g$ is the inductance of the transmission line, $C_g$ is the series-compensated capacitance of the transmission line.

![Figure 1. Series-compensated transmission system with a number of DFIGs.](image)

2.2. Small-signal model of DFIG and series-compensated transmission system
For DFIG-based series-compensated power system shown in Figure 2, the series-compensated network can be considered as an $RLC$ network with an impedance model $(R + sL + 1/sC)$. The small-signal model of DFIG and series-compensated transmission system is modeled in Figure 2.
Assume that the grid voltage is stable. As shown in Figure 2, the current \( I(s) \) can be expressed as

\[
I(s) = \frac{I_{DFIG}(s)Z_{DFIG}(s)}{Z_{DFIG}(s) + Z_{Grid}(s)} - \frac{V_{e}(s)}{Z_{DFIG}(s) + Z_{Grid}(s)}
\]

\[
= \left[ I_{DFIG}(s) - \frac{V_{e}(s)}{Z_{DFIG}(s)} \right] \frac{1}{1 + Z_{Grid}(s)/Z_{DFIG}(s)}
\]  (1)

If the system is stable, the denominator \( 1 + Z_{Grid}(s)/Z_{DFIG}(s) \) should have all zeros in the open left-half-plane. Based on Nyquist stability criterion, if and only if the number of counterclockwise encirclement around \((-1, j0)\) of \( Z_{Grid}(s)/Z_{DFIG}(s) \) is equal to the number of the right-half-plane (RHP) poles of \( Z_{Grid}(s)/Z_{DFIG}(s) \), the system will be stable.

From the above, the stability of system depends on \( Z_{Grid}(s)/Z_{DFIG}(s) \), which means that the stability is determined by both the impedance of grid and DFIG. Bode plots can be used to analyze the system stability. Bode plots of the grid impedance and the DFIG impedance can be placed together to identify the phase margin when the magnitudes of the two impedances are the same [5]. If the phase margin is less than zero, the system impedance characteristics is negative resistance and reactance, there will be the risk of SSR; in the contrary, if the phase margin is more than zero, the system impedance characteristics is positive resistance and reactance, the risk of SSR will be smaller.

2.3. Basics of the frequency scan method

According to the derivation from the previous section, the stability of the system is determined by the impedance of the grid \( Z_{Grid} \) and the DFIG \( Z_{DFIG} \) together. The impedance of grid \( Z_{Grid} \) can be calculated from the RLC network parameters. The impedance of DFIG \( Z_{DFIG} \) can be measured by the frequency scan method.

Frequency scan method is often used to measure the impedance. The impedance under different frequencies is widely used to represent the linearized characteristics of power system. A typical procedure of the frequency scan method is as following shown in Figure 3:

1. Make the DFIG running in a stable condition, then inject a small voltage perturbation signal. Record the \( V_0 + V_{test} \) and \( I_0 + I_{test} \) and the frequency of \( V_{test} \).
2. Perform FFT on \( V_{test} \) and \( I_{test} \), calculate the phasor \( V_{test} \), \( I_{test} \) at the frequency of \( V_{test} \), then calculate the DFIG impedance using \( Z_{total} = V_{test}/I_{test} \) and \( Z_{WTG} = Z_{total} - Z_{test} \).
3. Repeat step 1 to 2 by sweeping the perturbation in the frequency range of interest.
3. Case study

In this section, the impedance characteristics of different numbers of DFIGs are analyzed. Then the SSR characteristics under different DFIG numbers and parameters of series-compensated lines are compared.

This paper uses the DFIG model in RT-LAB for simulation. Voltage sources are used to represent the grid-side converters and the rotor-side converters instead of IGBTs. The rated power of the DFIG is 1.5MW. The wind speed is 9m/s. The model is shown in Figure 4. The main concern for the system is the impedance characteristics under different DFIG numbers and different parameters of series-compensated lines.

3.1. The impedance of DFIGs with different numbers

Different numbers including 20, 40, 60, 80, 100, 200, 300, 400 and 1000 DFIGs are scanned to study the impacts of DFIG numbers on the impedance characteristics. The resistances and reactances of the DFIGs under different numbers in 1-100Hz are shown in Figure 5.

As shown in Figure 5, the impedance curves of different numbers of DFIGs have the same trend. The impedance validation of 1/1000 Impedance of a single DFIG and impedance of 1000 DFIGs is presented in Figure 6.
As shown in Figure 6, the two impedances are approximately equal. Therefore, the impedance of N DFIGs can be roughly calculated as one of the 1/N of the impedance of one DFIG.

3.2. The SSR characteristics of DFIGs with different parameters of series-compensated lines

According to the derivation from the subsection 2.2, the stability of the system is determined by the impedance of the grid $Z_{\text{Grid}}$ and the DFIG $Z_{\text{DFIG}}$ together. In order to verify this derivation, two series-compensated lines of different parameters are used to study the SSR risk of the system under different line parameters and DFIG numbers. The parameters of two different series-compensated lines are shown in Tab.1.

| Parameters   | $R_g$  | $L_g$   | $C_g$  | Compensation degree |
|--------------|--------|---------|--------|----------------------|
| Line 1       | 0.484Ω | 1.5mH   | 0.008F | 19.85%               |
| Line 2       | 9.68Ω  | 30.8mH  | 0.0008F| 35.52%               |

3.2.1. The SSR characteristics of DFIGs with series-compensated Line 1. The bode plot of the impedance of different DFIG numbers and the series-compensated Line 1 are shown in Figure 7.

Figure 7 indicates that there exists a resonance risk around 9.0 Hz with 1000 DFIGs due to the negative phase margin of the system. As a comparison, there will be no resonance in Figure 7 when 100 DFIGs are connected to the series-compensated Line 1.

The simulation of 100 DFIGs with series-compensated Line 1 is presented in Figure 8. It illustrates that no resonance occurs and the system is stable, which is consistent with the impedance bode plot.
shown in Figure 7.

![Figure 8](image_url) Voltage of DFIG terminal and the line current with series-compensated Line 1 (100 DFIGs).

The simulation results of 1000 DFIGs with the series-compensated Line 1 is shown in Figure 9 to verify the above analysis. The system fundamental frequency is 50 Hz, and there is an additional resonance frequency at 9.6 Hz.

![Figure 9](image_url) Voltage of DFIG terminal and the line current with series-compensated Line 1 (1000 DFIGs).

3.2.2. The SSR characteristics of DFIGs with series-compensated Line 2. The bode plot of the impedance of different DFIG numbers and the series-compensated Line 2 are shown in Figure 10.

![Figure 10](image_url) Bode plot of impedance of different DFIG numbers and series-compensated Line 2.

Contrary to the series-compensated Line 1, Figure 10 indicates that there exists a resonance risk around 9.0 Hz with 100 DFIGs due to the negative phase margin of the system. As a comparison, there will be no resonance in Figure 10 when 1000 DFIGs are connected to the series-compensated Line 2.

The simulation results of 100 DFIGs with the series-compensated Line 2 is shown in Figure 11 to verify the above analysis. The system fundamental frequency is 50 Hz, and there is an additional resonance frequency at 9.3 Hz.
Figure 11. Voltage of DFIG terminal and the line current with series-compensated Line 2 (100 DFIGs).

The simulation of 1000 DFIGs with the series-compensated Line 2 is presented in Figure 12. It illustrates that no resonance occurs and the system is stable, which is consistent with the impedance bode plot shown in Figure 10.

Figure 12. Voltage of DFIG terminal and the line current with series-compensated Line 2 (1000 DFIGs).

3.2.3. Analysis on relationship between DFIG numbers and SSR characteristics. The bode plot of the impedance of different DFIG numbers and two different series-compensated lines are plotted in Figure 13. This figure indicates that the SSR frequency is related to both DFIG numbers and parameters of series-compensated lines.

Figure 13. Bode plot of impedance of different DFIG numbers and two series-compensated lines.

Relationship between DFIG numbers and phase margins of systems under two different parameters of series-compensated lines are shown in Figure 14.
As shown in Figure 14, the phase margin curves of systems under two different parameters of series-compensated lines have different trends. (1) The phase margin of system under Line 1 decreases with the increasing of DFIG numbers, which means with the increasing of DFIG numbers, the system becomes more unstable. (2) The phase margin of system under Line 2 first decreases and then increases with the increasing of DFIG numbers. The minimum value of the phase margin is less than zero. That is, as the number of DFIGs increases, the system varies from stable to unstable and finally becomes stable.

It can be concluded that the SSR risk of the system, is related with both the DFIG numbers and the parameters of series-compensated lines. In the case of different parameters of series-compensated lines, the relationship between the DFIG numbers and the SSR risk is not the same.

4. Conclusion
In this paper, the impedance characteristics of series-compensated transmission system with different DFIG numbers and different parameters of series-compensated lines are analyzed. The frequency scan method is applied to measure the DFIG impedance. The main conclusions are as follows:

1) The impedance of DFIGs decreases with the number of DFIG increases. The impedance of N DFIGs is roughly equal to 1/N of the impedance of one DFIG.

2) The SSR risk of the system, is related with both the numbers of DFIGs and the parameters of series-compensated lines. In the case of different parameters of series-compensated lines, the relationship between the DFIG numbers and the risk of SSR is not the same.

Future work includes the following aspects:
1) The impedance characteristics of DFIG with different SSR damping control strategies.
2) The parameter tuning method of SSR damping control strategies.

Appendix
The parameters of the DFIGs are as following:

| Parameter                      | Value 1 | Value 2 |
|--------------------------------|---------|---------|
| $K_{p(\text{GSC inner loop})}$ | 0.6     | 8       |
| $K_{p(\text{GSC outer loop})}$ | 8       | 0.6     |
| $K_{p(\text{RSC P control loop})}$ | 3       | 3       |
| $K_{p(\text{RSC Q control loop})}$ | 0.6     | 0.6     |
| $K_{p(\text{RSC } i_d \text{ control loop})}$ | 0.6     | 0.6     |
| $K_{p(\text{RSC } i_q \text{ control loop})}$ | 0.6     | 0.6     |

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