SSO Suppression Strategy of DFIG-Based Wind Turbine Based on Impedance Reshaping

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Abstract. In order to suppress the sub-synchronous oscillation (SSO) of DFIG-based wind power generation system, a new suppression strategy based on impedance reshaping is proposed in this paper. Firstly, the impedance model of DFIG-based wind power generation system set in static coordinate system is established, and the mechanism of SSO is analyzed through aggregated RLC equivalent circuit. Then, an impedance reshaping suppression strategy is proposed, the impedance model with additional suppression strategy is established, and its suppression mechanism is explained. Finally, the effectiveness of the impedance reshaping suppression strategy is verified by semi-physical experimental.

1. Introduction
With the rapid development of wind power generation, the stability of wind power integration system has received more attention. Most wind resources in China are far away from load center and require long-distance to transmit, so double-fed wind farms usually use series capacitor compensation to improve line transmission capacity, but which also brings the risk of SSO [1, 2].

At present, it is generally believed that the main cause of SSO in doubly-fed induction generator (DFIG) is sub-synchronous control interaction. Related studies have found that the converter control increases the negative impedance of the generator and exacerbates the induction generator effect, which leads to SSO [3, 4].

The interaction between inner and outer loop proportional coefficients of rotor side converter (RSC) on the SSO are analyzed, and the RSC virtual resistance controller suppression strategy is proposed in Ref. [5]; Based on active and reactive power analysis, additional damping control in RSC is proposed in Ref. [6]; A notch filter is added to the d-axis or q-axis of the current loop of RSC in Refs. [7, 8] to suppress SSO, and which proved the effectiveness of the proposed method by characteristic root analysis and simulation results. The above literatures analyzed the effect of RSC control on SSO deeply, and proposed additional damping control strategies, but there are still some deficiencies: The additional damping controls are all the additional virtual resistance, and ignored the influence of virtual inductance, which results when the series capacitor compensation of system is high, the more serious SSO occurs, and the oscillation convergence speed is slow, or even unable to converge.

Therefore, this paper proposes SSO suppression strategy of DFIG-based wind turbine based on impedance shaping. By inserting virtual impedance into RSC branch in series, the equivalent impedance of the system can be reshaped, so that the DFIG-based wind turbine system can realize the fast suppression of SSO in the harsh scenes such as high series capacitor compensation. Finally, the effectiveness of the proposed control strategy is verified by semi-physical experiments.
2. Impedance Modelling and Oscillation Mechanism of Doubly Fed Wind Turbine

2.1. Impedance Modeling of DFIG-Based Wind Turbine System

The structure of the DFIG-based wind turbine system is shown in figure 1, which including DFIG, transformer, transmission line, series compensation capacitor, etc. Among them, GSC and DFIG motor, RSC are connected by DC bus capacitors. Since the capacity of DC bus capacitor is usually large and the voltage fluctuation is small, the influence between the two can be ignored in impedance modeling, the impedance models of the two are established separately, and finally the total impedance of DFIG can be obtained in parallel, that is

\[ Z_{DFIG} = Z_{gsc} \parallel Z_{sator} \]  

(1)

In the formula, \( Z_{gsc} \) is the impedance of GSC; \( Z_{sator} \) is the impedance of DFIG motor and RSC.

![Figure 1. Composition of DFIG-based wind turbine system.](image)

The specific derivation process of DFIG impedance modeling has been described in many literatures at home and abroad [9], so this paper directly shows the formula of \( Z_{gsc} \) and \( Z_{sator} \).

\[ Z_{sator} = \frac{R_s + sL_s - \frac{s^2 L_s^2 \rho_m(s)}{R_s + sL_s \rho_m(s) + \frac{1}{s} I_{m}(s) + j \omega L_m} K_r^2}}{1 - F(s \mp j \omega_i)(1, H_{g}^*(s \mp j \omega_i) + \frac{D_r}{2} + j \frac{Q_{r0}}{2})} \]  

(2)

\[ Z_{gsc} = \frac{H_{g}^*(s \mp j \omega_i) + j K_{dq}^*}{1 - F(s \mp j \omega_i)(1, H_{g}^*(s \mp j \omega_i) + \frac{D_r}{2} + j \frac{Q_{r0}}{2})} \]  

(3)

In the formula, \( R_s \) and \( R_r \) are the resistance of the stator and rotor windings which converted to the stator side; \( L_s \) and \( L_r \) are the self-inductance of the stator and rotor windings; \( L_m \) is the mutual inductance between the stator and rotor windings; \( K_r \) is the turns ratio of stator and rotor windings; \( H_r(s) = K_{mp} + K_{pp}/s \), \( H_g(s) = K_{gp} + K_{pp}/s \) are the transfer function of the current inner loop PI regulator of RSC and GSC, \( K_{pp}, K_{mp}, K_{gp} \) are the ratio and integral coefficient of the PI regulators of RSC and GSC respectively; \( K_{dq}, K_{dp} \) are the decoupling coefficients of RSC and GSC current loops respectively, \( \omega_i \) and \( \omega_f \) are the slip angular frequency and fundamental angular frequency; \( I_{f} \), \( I_{i} \) are the fundamental frequency components of the DFIG rotor current and GSC output current; \( \rho_m(s) = (s - j \omega_f)/s \) is the slip coefficient in the frequency domain; \( \omega_f \) is the rotor electrical angular velocity; \( F(s) = H_{PLL}(s)/(1 + V_1 H_{PLL}(s)) \), Where \( H_{PLL}(s) = (K_{mp} + K_{pp}/s)/s \) is the transfer function of the phase-locked loop(PLL), \( K_{pp}, K_{mp} \) are the proportional and integral parameters of PI regulator in PLL, \( V_1 \) is the fundamental amplitude of grid voltage; \( D_{r0}, Q_{r0} \) and \( D_{n0}, Q_{n0} \) are the DC steady-state values output by the RSC and GSC current loops, and the formula can be seen in Ref. [9].

Therefore, the output impedance model of the DFIG-based wind turbine system including the total...
equivalent resistance $R_g$, equivalent reactance $L_g$ and series compensation capacitance $C$ of wind power transmission line and transformer is expressed as

$$Z = Z_{DFIG} + R_s + sL_s + \frac{1}{sC}$$  \hspace{1cm} (4)$$

2.2. Oscillation Suppression Mechanism Based on Aggregated RLC Stability Criterion

In this paper, the aggregation RLC stability criterion is used to study the SSO stability of DFIG-based wind turbine \[10\]: Through Thevenin theorem, complex circuits can be aggregated into RLC circuits, which is shown in figure 2.

![Figure 2. Aggregation RLC equivalent circuit.](image)

In figure 2, $R_{eq}$, $L_{eq}$, and $C_{eq}$ are the equivalent resistance, equivalent inductance, and equivalent capacitance of the system, and the natural oscillation frequency of the system is

$$f_e = \frac{1}{2\pi \sqrt{L_{eq}C_{eq}}}$$  \hspace{1cm} (5)$$

If the equivalent resistance $R_{eq}$ at the frequency $f_e$ is less than 0, the system will oscillate, otherwise the system is stable.

3. Oscillation Suppression Strategy Based on Impedance Reshaping

3.1. Impedance Model of DFIG-Based Wind Turbine with Additional Suppression Strategy

This paper proposes an impedance reshaping suppression strategy, that is, adding impedance reshaping control in RSC to make the $R_{eq}$ at oscillation frequency change from negative to positive, thereby achieving the purpose of suppressing SSO. The control strategy is shown in figure 3. In the figure, $K_r$ and $K_x$ are resistance and reactance reshaping control parameters respectively; $v_{rd,ssr}$ and $v_{rq,ssr}$ are the $d$-axis and $q$-axis control command of the new rotor voltage after added impedance reshaping control.

![Figure 3. Impedance reshaping suppression strategy.](image)

The rotor current in $dq$ coordinate system are selected as the input of additional control, and its fundamental wave component is DC in $dq$ coordinate system. First, the fundamental component of the input current is calculated by the Fourier analysis of filter, and then the input current is subtracted from
the calculation result to obtain the current with only the sub-synchronous component. The filter is shown in figure 4.

\[
\text{Fourier Analysis}
\]

\[
\text{Dc component}
\]

\[
\text{Input current} \quad \text{Output current}
\]

\[
\frac{1}{T} \int_{-T/2}^{T/2} i(t) \, dt = \frac{1}{T} \int_{-T/2}^{T/2} \frac{2}{T} \int_{-T/2}^{T/2} \cos(\omega t) \, dt
\]

\[
\text{Dc component}
\]

\[
\text{Input current} \quad \text{Output current}
\]

\[
\text{Filter design}
\]

Finally, the filtered input current is multiplied by the corresponding additional impedance reshaping control parameters to obtain additional control signals. According to the derivation process of impedance model in [9], after adding impedance remodeling control, the expression of \( Z_{\text{rotor}} \) changes to equation (6), and that of \( Z \) changes to equation (7).

\[
Z_{\text{rotor}} = \frac{R_s + sL_s - s^2 L_s \rho_{\text{rotor}}(s)}{R_r + sL_r + [H_r(s + j\omega_l) - K_{\text{rotor}} + j(K_{\text{rotor}} + K_{\text{grid}})K_s^2]}
\]

\[
1 - \frac{sL_r F(s + j\omega_l) \{1 + [H_r(s + j\omega_l) - K_{\text{rotor}} + j(K_{\text{rotor}} + K_{\text{grid}})] + \frac{D_{\text{vol}}}{2} + j \frac{Q_{\text{vol}}}{2} \} K_s}{R_r + sL_r \rho_{\text{rotor}}(s) + [H_r(s + j\omega_l) - K_{\text{rotor}} + j(K_{\text{rotor}} + K_{\text{grid}})K_s^2]}
\]

\[
Z = \frac{Z_{\text{grid}}}{Z_{\text{rotor}}} + R_g + sL_g + \frac{1}{sC}
\]

3.2. Suppressing Mechanism of Impedance Reshaping Control

The main operating parameters of DFIG-based wind turbine are shown in table 1.

| Parament       | Value       | Parament       | Value       |
|----------------|-------------|----------------|-------------|
| \( R_s \)      | 0.023pu     | \( R_r \)      | 0.016pu     |
| \( L_m \)      | 2.9pu       | \( L_s \)      | 3.08pu      |
| \( L_r \)      | 3.06pu      | \( L_{\text{grid}} \) | 0.0315 H |
| \( R_{\text{grid}} \) | 3.459 Ω   | \( L_{\text{filter}} \) | 0.3pu      |
| \( K_{\text{rp}} \) | 0.6     | \( K_{\text{ri}} \) | 8          |
| \( K_{\text{gp}} \) | 0.83    | \( K_{\text{gi}} \) | 5          |
| Active power   | 1.5 MW      | DFIG numbers   | 6          |
| \( U_{\text{dc}} \) | 1150 V   | DC capacitance | 10 mF      |
| Wind speed     | 15 m/s      | frequency      | 60 Hz       |
| Line length    | 30 km       | Line resistance| 0.115 Ω/km |
| Line reactance | 0.00105 H/km| \( C_{\text{grid}} \) | 0.56 mF    |

3.2.1. Resistance Reshaping Control. The resistance reshaping controller extracts the sub-synchronous component of the rotor current and multiplies it by the resistance reshaping control parameters \( K_r \) to feed back to the RSC output. In order to analyze the influence of additional resistance controller on the stability of the system, it is necessary to draw the SSO characteristic curve when \( K_r \) changes. At this
time, the reactance reshaping control reactance control is not added, so $K_x=0$.

![Figure 5](image)

**Figure 5.** Characteristic curve of system sub-synchronous oscillation when $K_r$ changes.

According to equation (7), figure 5 plots the oscillation frequency $f_p$ of the system and the equivalent resistance $R_{eq}$ of the system at $f_p$ when $K_r$ takes different values (taking 0 means no additional control is introduced) when only additional resistance remodeling control is used. It can be seen from the figure that when $K_r=0, R_{eq}=-0.0024<0$. According to RLC stability criterion, the system is unstable without additional suppression strategy and the SSO cannot be suppressed. With the increase of $K_r$ value, the $f_p$ of the system changes slightly. The equivalent resistance of the system at $f_p$ gradually changes from negative to positive, equivalent to inserting a positive resistance in the RSC branch, and the system gradually stabilizes.

3.2.2. Reactance Reshaping Control. Same as section 3.2.1, figure 6 shows the $f_p$ of the system and the $R_{eq}$ of the system at $f_p$ when $K_x$ takes different values (0 means no additional control is introduced) when only additional reactance reshaping control is used. At this time, the resistance reshaping control is not added, so $K_r=0$. It can be seen from the figure that as the value of $K_x$ increases, the $f_p$ gradually decreases, making the $R_{eq}$ of the system at $f_p$ gradually increase, and the system gradually enters the stable state from the unstable state. The larger the value of $K_x$ is, the larger the inductance in series in the RSC branch, so the greater the equivalent reactance of the system.

3.2.3. Additional Control Parameter Value Limit. When the value of $K_r$ or $K_x$ is too large, the stability of the control system will be reduced, and the oscillation will not converge. Taking the resistance reshaping control as an example, figure 7 shows the active power waveform of the DFIG grid-connected system when $K_r$ changes (see table 1 for system operating parameters). With the increase of $K_r$ value from 0.12 to 0.22, the SSO of active power changes from slow convergence to fast convergence. When $K_r$ continues to increase to 0.35, the oscillation cannot converge, and the continuous increase of $K_r$ will lead to system instability and abnormal operation.

Therefore, the value of $K_r$ or $K_x$ cannot be too large, which results in the limited suppression ability of a single additional control (only resistance reshaping control or reactance reshaping control is introduced). Faced with severe SSO, it is necessary to adopt impedance reshaping suppression strategy (resistance reshaping control and reactance reshaping control are all introduced).
4. Semi-physical Experiment Verification

A semi-physical experimental platform of DFIG system is built based on RT-LAB real-time simulator and RCP real-time controller, which is shown in figure 8. The model parameters are shown in table 1 (the values of series compensation capacitor $C_{\text{grid}}$ are different).

Figure 6. Sub-synchronous oscillation characteristic curve when $K_x$ changes.

Figure 7. Active power waveform of DFIG-based wind turbine system with different $K_r$.

Figure 8. Semi-physical experiment platform.
4.1. Additional Single Control Parameter Verification

In this section, the effectiveness of single resistance and reactance control parameters is verified by semi-physical experiments. The simulation condition is that the system operates normally before 6 seconds, and the active power output is constant at 9 MW. At 6 seconds, the series compensation capacitor $C_{\text{grid}}=1\text{mF}$ is put into the transmission line. The following figures 9 to 11 all show the active power waveform after the series compensation put into.

Without additional control, the system generates SSO with a frequency of 16 Hz, and the corresponding active power oscillation frequency is 44 Hz, as shown in figure 9. From 6 s to 6.4 s, due to the negative $R_{eq}$ of the system, the active power presents an amplitude oscillation state with a maximum amplitude of 10.75 MW. After 6.4 s, due to the saturation of the excitation reactance flux, it enters the state of equal amplitude oscillation.

The suppression effect of the additional resistance reshaping control parameter $K_r$ is shown in figure 10. The system oscillation is quickly suppressed with a maximum amplitude of 10.15MW. After 6.18 s, it returns to a stable operating state.

The suppression effect of the additional reactance reshaping control parameter $K_x$ is shown in figure 11. The system oscillation can converge, with a maximum amplitude of 9.84 MW, but the convergence rate is slow. After 6.4 s, the active power oscillation amplitude weakens to ±1%.

![Figure 9. Active power waveform of DFIG-based wind turbine without additional control.](image)

![Figure 10. Active power waveform of DFIG-based wind turbine system with $K_r$.](image)

![Figure 11. Active power waveform of DFIG-based wind turbine system with $K_x$.](image)

From the above experimental results, it can be seen that when a SSO with a low frequency occurs in the system, only resistance or reactance reshaping control can suppress the SSO. The oscillation convergence of resistance reshaping control is the faster than that of reactance reshaping control, but the maximum amplitude is higher.

4.2. Impedance Remodeling Suppression Verification

This section uses semi-physical experiment to verify the effectiveness of the impedance reshaping suppression strategy when the system series compensation increases and more serious SSO occurs. The simulation conditions are similar to the section 4.1, except that the series compensation capacitor $C_{\text{grid}} = 0.25 \text{ mF}$.

When there is no additional control, series compensation capacitor is put into operation in 6s, and the system generates SSO oscillation with an oscillation frequency of 32Hz, as shown in figure 12. The active power exhibits a state of increasing amplitude oscillation and then equal amplitude oscillation. The maximum amplitude is 20 MW, the oscillation is violent, and the impact on the power grid is more severe.
When adding the resistance reshaping control, and select different $K_r$ for experiment (increase the value of $K_r$ until it causes other oscillations), and the control effect is shown in figure 13 when $K_r$ has the best oscillation suppression effect. In figure 13, the maximum amplitude is reduced to 16MW, although the amplitude is weakened, there is still an equal-amplitude oscillation with an amplitude of about ±4MW after 6.18s, which cannot suppress the oscillation.

The suppression effect of the additional impedance reshaping control parameters $K_r$ and $K_x$ is shown in figure 14. The system oscillation is suppressed quickly, and the maximum amplitude is 14.1MW, after 6.2s, the system restores to stable operation.

![Figure 12. Active power waveform of DFIG-based wind turbine without additional control.](image1)

![Figure 13. Active power waveform of DFIG-based wind turbine system with $K_r$.](image2)

![Figure 14. Active power waveform of DFIG-based wind turbine system with $K_r$ and $K_x$.](image3)

From the above experimental results, it can be seen that when the system has a high frequency of SSO that has a higher amplitude and the more serious situation, only a single reshaping control (resistance or reactance) cannot suppress the SSO; Impedance reshaping suppression strategy can maximize the ability to suppress the SSO of DFIG. In the face of more serious SSO, it can still make the oscillation converge quickly.

5. Conclusions

Aiming at the problem of SSO of DFIG, this paper proposes the impedance reshaping suppression strategy, and finally verifies the correctness and effectiveness of the proposed control strategy through semi-physical experiment. Compared with traditional SSO suppression strategies, SSO suppression ability is improved. The proposed strategy can still effectively suppress SSO in the case of high series compensation.

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References

[1] Dong X L, Tian X, Zhang Y, et al. 2017 Practical SSR incidence and influencing factor analysis of DFIG-based series-compensated transmission system in Guyuan farms High Voltage Engineering 43 (1) 321-8.

[2] Xu D K 2018 Research on the control scheme to damping DFIG-associated SSR on the grid side in Guyuan wind farms.
[3] Irwin G D, Jindal A K and Isaacs A L 2011 Sub-synchronous control interactions between type 3 wind turbines and series compensated AC transmission systems Power & Energy Society General Meeting.

[4] Mohammadpour H 2014 Sub-synchronous resonance analysis in DFIG-based wind farms: Definitions and problem identifications-part I IEEE Energy Conversion Congress and Exposition (ECCE), IEEE.

[5] Wu X, Guan Y J, Ning W, et al. 2018 Mechanism of interactive effect of RSC parameters in DFIG on SSO and its application Power System Technology 42 (8).

[6] Li H, Chen Y J, Zhao B, et al. 2014 Reactive power control of sub-synchronous oscillation damping system for DFIG-based wind farms Electric Power Automation Equipment 34 (12) 19-25.

[7] Liu H K, Xie X R, He J, et al. 2016 Damping DFIG-associated SSR by adding sub-synchronous suppression filters to DFIG converter controllers 2016 IEEE Power and Energy Society General Meeting (PESGM).

[8] Liu H K, Xie X R, Li Yu, et al. 2015 Damping DFIG-associated SSR with sub-synchronous suppression filters: A case study on a practical wind farm system IEEE International Conference on Renewable Power Generation, Beijing, China pp 1-6.

[9] Yang H Y 2016 Impedance Modeling and Stability Analysis of Doubly Fed Induction Generator System (Zhejiang University).

[10] Nian H and Yang H Y 2016 Impedance modeling and stability analysis of grid connected inverter under unbalanced operation Automation of Electric Power Systems 40 (10) 76-83.