Research on the Sub-synchronous Oscillation in Wind Power Connected to Series Compensated Power System and its Influencing Factors

Chao Gao, Hui Liu, Hao Jiang, Yunhong Li, and Xisheng Tang

Abstract—When wind farms, which is based on double fed induction generator (DFIG), are connected to the series compensation power system, the phenomenon of sub-synchronous oscillation (SSO) may occur. In order to study the sub-synchronous oscillation in wind power connected to series compensated power system and its influencing factors, we used RT-LAB to establish a simulation model concerning wind power connected to series-compensation power system. This model take a wind power connected to series compensation power system in north China as prototype. All influence factors of wind power SSO are simulated and analyzed by using time domain analysis method. The simulation results show that the effects of wind speed, series compensation degree and proportional control coefficient of rotor side converter (RSC) are most obvious.

Index Terms—Double fed induction generator, influence factors, interaction of SSO, sub-synchronous oscillation, series compensation.

I. INTRODUCTION

The series-compensated technologies can significantly improve the power system stability and its transmission capacity [1], but it has potential risks to induce SSO as well [2]. Recently, the phenomenon of SSO on the series compensated power system has been well researched. Induction generator effect (IGE), sub-synchronous control interaction (SSCI) and torsional amplification are regard as the most common influencing factors [3]. These phenomena also exist in wind power connected to series-compensated power system [4]. The SSO of wind power connected to series-compensated power system was first found in the USA. In October 2009, a wind power connected to series-compensation power system in Texas occur a SSO accident [5]-[7]. This phenomenon was also found in North China in 2012 [8]. Therefore, this kind of SSO problems caused widespread concern of the power system researchers.

At present, some research results on the problem of SSO caused by wind power connected to series-compensated power system have been obtained. Limebeer and Harley discussed that induction motor type wind power generator had opportunities to cause SSO [9] and proved this conclusion through time domain simulation. Literature [10] establishes a simulation model including doubly fed wind turbines and series compensation system by PSCAD, deduced the corresponding small signal analysis model, and explained the influence of various factors’ changing on system stability. But it did not specified the main reasons inducing SSO. The research on the leading cause of SSO is pointed out in paper [11]-[16]. The paper [11] finds that the greater the outputs power from the wind farm is, the smaller the system damping will be, and the SSO is more serious. The paper [12] finds that the stability of wind power connected to series-compensated power system was influenced by wind speed and control parameter of wind power. Fan Linlin and Miao Zhixin used the modal analysis method and the factor binding integrated root locus analysis method respectively and pointed out that IGE was the leading cause of SSO [13-15]. They deduced the relationship between electromagnetic torque and rotating speed [16], and discussed the influence of various factors on sub-synchronization characteristics. Literature [17] analyzes the influence of wind speed and output power on sub-synchronization characteristics under wind turbine operation region, and also introduced the concept of stability region intensively. The number of wind turbines had influence on SSO in wind power connected to series-compensated power system [18]. The literature [19] uses the modal analytical approach to obtain the participation factor of the wind power connected to series-compensation power system when the system causes SSO. The effect of wind speed on the sub-synchronous oscillation of the wind power connected to series-compensation power system was analyzed by simulation [20], but it did not carry out theoretical analysis.

Generally speaking, the existed research achievements are mainly based on the influence of control parameters on the rotor side converter (RSC), and most of RSC is set into stator flux control mode in the analysis. This analysis is not comprehensive enough. Stator flux control is only one of the RSC control mode. Stator voltage oriented control is also the common control mode. When considering the influence of control parameters, the control parameters of grid side converter (GSC) should also be considered at the same time.

We take a wind power connected to series compensation power system in north China as prototype. Firstly, this paper analyzes the SSO mechanism of wind power connected to series-compensation power system. Secondly, this paper builds
the power system real-time simulation model by RT-LAB. At last, we use the simulation model to analyze the main influence factors of sub-synchronous oscillation in wind power connected to series-compensated power system. We can get that the factors of wind speed, compensation degree, control parameters of RSC and GSC leading to SSO of power system contained wind power. And the wind speed, series compensation degree and the proportional coefficient of speed loop control for RSC have most significant impact on the power system SSO among all the influencing factors.

II. POWER SYSTEM MODELING

This paper selected a certain power system in north China as prototype, whose load center powered by double circuited 500kV line from the far power supply side, and the double circuits were all added in series capacitor compensation. The wind farm’ installed capacity was about 3000MVA, and it composed of DFIGs which terminal voltage was 690V and capacity was 1.5MVA. This DFIG boost voltage through 0.69/35kV, 35/220kV and 220/500kV line transformers successively, and then connects to the power system. If considering the low voltage transmission line’ impedance, the equivalent leakage reactance of DFIG's rotor fulfills about 1.97%. The whole wind farm can be equivalent to a double fed induction generator when wind turbines’ operating conditions almost the same [21]. The power system model is shown in Fig. 1.

Fig. 1. Equivalent circuit of the wind farm connected to a series-compensated system.

In this Fig. , \( X_L \) is the equivalent reactance, \( R_L \) is the equivalent resistance, and \( X_r \) is the series compensation capacitor. This paper analyzed the main factors of leading to SSO of wind power connected to series-compensation power system.

From Fig. 1, we can get the sub-synchronous frequency \( f_s \) fulfills publicity (1).

\[
f_s = f_0 \sqrt{\frac{X_L}{X_r}} \tag{1}
\]

In publicity (1), \( f_0 \) is the power system frequency, and it fulfills \( f_0 = 50Hz \).

III. MECHANISM OF SSO IN POWER SYSTEM CONTAINED WIND POWER

The DFIG has its particular control system, so the SSO problems mainly are induction generator effect (IGE) and sub-synchronous control interaction (SSCI) when it is connected to the power system through series compensation line [8, 22-23]. Under the sub-synchronous frequency, the rotor slip of doubly fed induction generator (DFIG) is:

\[
s_o = \frac{f_r - f_s}{f_s} \tag{2}
\]

In publicity (2), \( f_r \) is wind turbine’s rotor frequency, \( f_s = (1-s_o)f_1 \), and \( s_o \) is initial operation slip of the wind turbine. The rotor speed changes small in a short period of current oscillation time, so it can be regarded as a constant. In normal circumstances, \( f_s < f_r \), so \( s_o < 0 \).

Without considering the influence of RSC, using frequency scanning method to analyze the IGE system, the equivalent circuit is as Fig. 2.

Fig. 2. Equivalent circuit for IGE analysis.

In Fig. 2, \( R_{eq} \) is equivalent resistance of DFIG’s rotor, \( X_{as} \) is equivalent leakage reactance of DFIG’s stator, \( X_{ar} \) is equivalent leakage reactance of DFIG’s rotor, \( X_f = X_{fs} + X_{fr} \).

When the frequency is sub-synchronous frequency, the equivalent resistance of DFIG’s rotor fulfills \( R_{eq} = R_r/ s_o < 0 \), and

\[
\frac{|R_{eq}|}{|s_o|} = \frac{R_r}{|1 - f_s/f_r|} = \frac{R_r}{f_r/f_s - 1} \tag{3}
\]

Therefore, under the sub-synchronous frequency, \( R_{eq} < 0 \), and \( |R_{eq}| \) enlarge with \( f_s \) increase and with \( f_r \) reduce. When \( |R_{eq}| \) is bigger than the sum of equivalent resistance of stator and equivalent resistance of transmission system in this resonant frequency, the whole system’s resistance value is negative, which will lead to continuous divergence oscillation of the line current. In other words, the system will have the phenomenon of IGE.

There is a certain relationship between the output power of wind turbine and wind speed. The optimal rotation speed of wind turbine is varied from different wind speed, as shown in Fig. 3.

Fig. 3. Relationship between active power output and rotor speed of wind turbine.
From Fig. 3, we can know that wind turbine needs to match to the optimum rotation speed ($\omega_{\text{m,appr}}$) to obtain the maximum output power, thus a corresponding generator rotor frequency ($f_{r,\text{m,appr}}$) is existence, and $f_{r,\text{m,appr}} = \omega_{\text{m,appr}}/2\pi$. In Fig. 3, $v_1 < v_2 < v_3$, with the increasing of $v$, $\omega_{\text{m,appr}}$ increases gradually, and $f_{r,\text{m,appr}}$ also increases.

From publicity (1) we can know that $f_{r,\text{m,appr}}$ increases with the increasing of series compensation. From Fig. 3, we can know that $f_r$ reduces with the reducing of wind speed. They can lead to $|R_{r,sy}|$ increase, and cause the system damping value increase, and intensify SSO of system. In other words, IGE is related to the degree of line compensation and wind speed. The increase of series compensation and the decrease of wind speed cause the occurrence of IGE possibly.

SSCI refers to SSO caused by the frequency converter control system of DFIG. When DFIG stator current exists oscillatory component of sub-synchronous frequency, GSC continued to run and maintain a constant direct current bus voltage. Therefore, it can be considered that GSC control has little effect on sub-synchronous current. However, the instantaneous power and instantaneous current (i) of RSC will change all the time, so RSC control will result in the change of rotor voltage ($u_s$) of DFIG. The change of $u_s$ can react to i, so the change of inducted stator current will produce new sub-synchronous current.

Fig. 4 shows the process of wind power system control leading to SSO.

New sub-synchronous current component superimposed on original disturbance current component, when represented by vectors, if their phase shift is less than 90°, the original disturbance current will increasing due to the superposition theorem of vector. At this time, the sub-synchronous current gradually increase due to positive feedback effect, and the RSC and GSC control system of DFIG can form mutual incentive with series compensated circuits. They may lead the active and reactive power output of DFIG to happen oscillation divergence, so the system generates SSCI. Therefore, changing control parameters of RSC and GSC can affect SSO of power system.

IV. SIMULATION ANALYSES

A. Influences of wind speed changing on SSO

Based on the power system model built in the first chapter, we carried out simulation and analysis of SSO under different wind speed. Series compensation of power system was 1.95%. Wind speed was 6m/s, 7m/s, 8m/s, 9m/s, 10m/s in turn. Series capacitors input in 6s. The torque outputs of wind turbine are shown in Table I.

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>Steady state torque</th>
<th>Maximum torque</th>
<th>Minimum torque</th>
<th>Maximum torque shift</th>
<th>Stable time</th>
</tr>
</thead>
<tbody>
<tr>
<td>6m/s</td>
<td>0.125p.u.</td>
<td>0.270p.u.</td>
<td>0.000p.u.</td>
<td>0.145p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>7m/s</td>
<td>0.215p.u.</td>
<td>0.345p.u.</td>
<td>0.050p.u.</td>
<td>0.130p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>8m/s</td>
<td>0.280p.u.</td>
<td>0.360p.u.</td>
<td>0.220p.u.</td>
<td>0.080p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>9m/s</td>
<td>0.361p.u.</td>
<td>0.400p.u.</td>
<td>0.315p.u.</td>
<td>0.046p.u.</td>
<td>2.1s</td>
</tr>
<tr>
<td>10m/s</td>
<td>0.450p.u.</td>
<td>0.495p.u.</td>
<td>0.405p.u.</td>
<td>0.045p.u.</td>
<td>1.2s</td>
</tr>
</tbody>
</table>

The SSO phenomenon gradually weakened with the increasing of wind speed in TABLE I. When the wind speed is less than 9m/s, the interaction of sub-synchronous control is strong, which lead to the divergence of wind turbine generators torque. When the wind speed is higher than 9m/s, series capacitors’ input causes wind turbine torque oscillation, but the oscillation amplitude is small and quickly tended to converge, and the system restores stability eventually. The simulation results meets to the theoretical analysis in the second chapter.

B. Influences of series compensation degree changing on SSO

In the basic of power system model built in first chapter, the simulation analysis was carried out for power system SSO under different series compensation degrees. The wind speed was 9m/s, and the series compensation degree was 0.5%, 1%, 1.5%, 2%, 2.5%, 3% in turn. Series capacitors input in 6s. The torque outputs of wind turbine are shown in Table II.

<table>
<thead>
<tr>
<th>Series compensation degree</th>
<th>Steady state torque</th>
<th>Maximum torque</th>
<th>Minimum torque</th>
<th>Maximum torque shift</th>
<th>Stable time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5%</td>
<td>0.361p.u.</td>
<td>0.375p.u.</td>
<td>0.348p.u.</td>
<td>0.014p.u.</td>
<td>0.6s</td>
</tr>
<tr>
<td>1.0%</td>
<td>0.361p.u.</td>
<td>0.383p.u.</td>
<td>0.338p.u.</td>
<td>0.023p.u.</td>
<td>0.8s</td>
</tr>
<tr>
<td>1.5%</td>
<td>0.361p.u.</td>
<td>0.391p.u.</td>
<td>0.331p.u.</td>
<td>0.030p.u.</td>
<td>1.2s</td>
</tr>
<tr>
<td>2.0%</td>
<td>0.361p.u.</td>
<td>0.403p.u.</td>
<td>0.314p.u.</td>
<td>0.047p.u.</td>
<td>2.3s</td>
</tr>
<tr>
<td>2.5%</td>
<td>0.361p.u.</td>
<td>0.415p.u.</td>
<td>0.313p.u.</td>
<td>0.048p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>3.0%</td>
<td>0.361p.u.</td>
<td>0.495p.u.</td>
<td>0.225p.u.</td>
<td>0.136p.u.</td>
<td>Divergence</td>
</tr>
</tbody>
</table>

When the series compensation degree is small, the coming of the fixed capacitor suddenly has a small effect and wind turbine torque converged after oscillation rapidly in the TABLE II. The interaction of sub-synchronous control gradually enhances with the increasing of the of series compensation degree. When the series compensation degree is more than 2.5%, the torque...
oscillation is rapidly divergent. The simulation agrees with the theoretical analysis in the second chapter.

C. Influences of GSC control parameters changing on SSO

In the basic of power system model built in first chapter, the simulation analysis was carried out for power system SSO under different control parameters of GSC.

In Fig. 5, $K_{p1}$ was proportional coefficient and $K_1$ was integral coefficient of DC bus voltage control for GSC, $K_{p2}$ was proportional coefficient and $K_2$ was integral coefficient of DC bus current control for GSC. The simulation analysis was carried out for wind turbine torque under different GSC control parameters, when power system series compensation degree was 1.95% and wind speed was 8 m/s.

1) $K_{p1}$, $K_{p2}$, $K_{12}$ unchanged and $K_{p1} = 1$, $K_{p1} = 5$, $K_{p1} = 15$ in turn, simulation and analysis of torque variations of wind turbine generator are shown in Table III.

2) $K_{p1}$, $K_{p2}$, $K_{12}$ unchanged and $K_{p1} = 100$, $K_{p1} = 400$, $K_{p1} = 800$ in turn, simulation and analysis of torque variations of wind turbine generator are shown in Table IV.

3) $K_{p1}$, $K_{p2}$, $K_{12}$ unchanged and $K_{p2} = 0.5$, $K_{p2} = 1$.

4) $K_{p1}$, $K_{p2}$, $K_{12}$ unchanged and $K_{p1} = 0.1$, $K_{p1} = 1$, $K_{p2} = 10$ in turn, simulation and analysis of torque variations of wind turbine generator are shown in Table V.

5) $K_{p1}$, $K_{p2}$, $K_{12}$ unchanged and $K_{p2} = 5$ in turn, simulation and analysis of torque variations of wind turbine generator are shown in Table VI.
It can be known from TABLE VI that the integral coefficient of DC bus current control for GSC has a certain influence on the torque of wind turbine generator. With the increase of \( K_{p3} \), the torque oscillation of wind turbine reduced.

All in all, the torque oscillation of wind turbine reduced with the increase of \( K_{p4} \) or \( K_{i2} \), and with the reduce of \( K_{p2} \), while \( K_{i0} \) just have a little effect on torque oscillation.

**D. Influences of RSC control parameters changing on SSO**

In the basic power system model built in first chapter, the simulation analysis was carried out for power system SSO under different control parameters of RSC.

In Fig. 6, \( K_{p3} \) was proportional coefficient and \( K_{i3} \) was integral coefficient of speed loop control for RSC, \( K_{p4} \) was proportional coefficient and \( K_{i4} \) was integral coefficient of current control for RSC. The simulation analysis was carried out for wind turbine torque under different RSC control parameters, when power system series compensation degree was 1.95% and wind speed was 8m/s.

**TABLE VII**

<table>
<thead>
<tr>
<th>( K_{p3} )</th>
<th>Steady state torque</th>
<th>Maximum torque</th>
<th>Minimum torque</th>
<th>Maximum torque shift</th>
<th>Stable time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.275p.u.</td>
<td>0.295p.u.</td>
<td>0.255p.u.</td>
<td>0.020p.u.</td>
<td>2.8s</td>
</tr>
<tr>
<td>5</td>
<td>0.275p.u.</td>
<td>0.495p.u.</td>
<td>0.075p.u.</td>
<td>0.220p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>10</td>
<td>0.275p.u.</td>
<td>0.655p.u.</td>
<td>0.000p.u.</td>
<td>0.380p.u.</td>
<td>Divergence</td>
</tr>
</tbody>
</table>

It can be known from TABLE VII that the proportional coefficient of speed loop control for RSC has a certain influence on the torque of wind turbine generator. With the increase of \( K_{p3} \), the torque oscillation of wind turbine enhanced.

(2) \( K_{p3} \), \( K_{p4} \), \( K_{i4} \) unchanged and \( K_{i3} = 0.3 \), \( K_{i3} = 0.6 \), \( K_{i3} = 0.9 \) in turn, simulation and analysis of torque variations of wind turbine generator are shown in TABLE VIII.

**TABLE VIII**

<table>
<thead>
<tr>
<th>( K_{i3} )</th>
<th>Steady state torque</th>
<th>Maximum torque</th>
<th>Minimum torque</th>
<th>Maximum torque shift</th>
<th>Stable time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.275p.u.</td>
<td>0.405p.u.</td>
<td>0.165p.u.</td>
<td>0.130p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>0.6</td>
<td>0.275p.u.</td>
<td>0.355p.u.</td>
<td>0.225p.u.</td>
<td>0.080p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>0.9</td>
<td>0.275p.u.</td>
<td>0.305p.u.</td>
<td>0.245p.u.</td>
<td>0.030p.u.</td>
<td>Divergence</td>
</tr>
</tbody>
</table>

It can be known from TABLE VIII that the integral coefficient of speed loop control for RSC has a certain influence on the torque of wind turbine generator. With the increase of \( K_{i3} \), the torque oscillation of wind turbine reduced.

(3) \( K_{p3} \), \( K_{i3} \), \( K_{i4} \) unchanged and \( K_{p4} = 0.1 \), \( K_{p4} = 1 \), \( K_{p4} = 10 \) in turn, simulation and analysis of torque variations of wind turbine generator are shown in TABLE IX.

**TABLE IX**

<table>
<thead>
<tr>
<th>( K_{p4} )</th>
<th>Steady state torque</th>
<th>Maximum torque</th>
<th>Minimum torque</th>
<th>Maximum torque shift</th>
<th>Stable time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.275p.u.</td>
<td>0.355p.u.</td>
<td>0.235p.u.</td>
<td>0.080p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>1</td>
<td>0.275p.u.</td>
<td>0.355p.u.</td>
<td>0.235p.u.</td>
<td>0.080p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>10</td>
<td>0.275p.u.</td>
<td>0.355p.u.</td>
<td>0.235p.u.</td>
<td>0.080p.u.</td>
<td>Divergence</td>
</tr>
</tbody>
</table>

It can be known from TABLE IX that the proportional coefficient of current control for RSC has a little effect on the torque of wind turbine generator.

(4) \( K_{p3} \), \( K_{i3} \), \( K_{p4} \) unchanged and \( K_{i4} = 1 \), \( K_{i4} = 4 \), \( K_{i4} = 8 \) in turn, simulation and analysis of torque variations of wind turbine generator are shown in TABLE X.

**TABLE X**

<table>
<thead>
<tr>
<th>( K_{i4} )</th>
<th>Steady state torque</th>
<th>Maximum torque</th>
<th>Minimum torque</th>
<th>Maximum torque shift</th>
<th>Stable time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.275p.u.</td>
<td>0.335p.u.</td>
<td>0.240p.u.</td>
<td>0.060p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>4</td>
<td>0.275p.u.</td>
<td>0.345p.u.</td>
<td>0.230p.u.</td>
<td>0.070p.u.</td>
<td>Divergence</td>
</tr>
<tr>
<td>8</td>
<td>0.275p.u.</td>
<td>0.365p.u.</td>
<td>0.220p.u.</td>
<td>0.080p.u.</td>
<td>Divergence</td>
</tr>
</tbody>
</table>
It can be known from table 10 that the integral coefficient of
current control for RSC has a certain influence on the torque of
wind turbine generator. With the increase of $K_{i4}$, the torque
oscillation of wind turbine enhanced.

All in all, the torque oscillation of wind turbine enhanced with
the increase of $K_{j3}$ or $K_{i4}$, and with the reduce of $K_{j3}$,
while $K_{p4}$ just have a little effect on torque oscillation.

V. SUMMARY AND CONCLUSION

The main influence factors of sub-synchronous oscillation
in wind power connected to series-compensated power system
are analyzed in this paper. It is shown that wind speeds, series
compensation degrees, control parameters of GSC and RSC all
influence the SSO of the wind power connected to
series-compensated power system.

By increasing of wind speed, $K_{p1}$, $K_{p2}$, $K_{j3}$ can suppress the
SSO phenomenon of power system.

Through increasing of
series compensation degree, $K_{p2}$, $K_{p3}$, $K_{i4}$ can exacerbate the
SSO phenomenon of power system. $K_{j1}$ and $K_{p4}$ have little

effects on power system SSO.

Wind speed, series compensation degree and $K_{p3}$ have most

significant impact on the power system SSO among all the
influencing factors.

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