INTRODUCTION
Subsynchronous oscillation is the continuous and even increasing oscillation caused by the coupling of the dynamic processes in mechanical equipments and electrical equipments in the power system, which is one of the problems of power system stability[1]. The study of subsynchronous oscillation began in the 1930s. The early research is mainly related to the thermal power system. In recent years, the scope of subsynchronous oscillation has been expanded with the continuous development of wind energy utilization. Since 2011, subsynchronous oscillation has occurred many times in North China DFIG wind farms connected to grid by series compensation facilities[2]. The emergence of these problems seriously influences the safe and stable operation of the power system as well as the development and utilization of wind energy. Under this circumstance, it is necessary to further study the mechanism, manifestations, control strategies and other issues of subsynchronous oscillation.

At present, domestic and foreign research on subsynchronous oscillation in wind power grid-connected system have made some achievements. In the literature [3], the model of DFIG wind farm system connected to grid by series compensation is established, and the mechanism and influencing factors of the subsynchronous oscillation are analyzed by frequency scanning method. But it does not involve the study of subsynchronous oscillation control methods. In the literature [4-6], the subsynchronous oscillation is reconstructed by simulation. The dominant factors are wind speed, generator number in service, series compensation level and wind turbine controller, analyzed by system eigenvalues and impedance. But they focus on analyzing the impact of changes in factors on subsynchronous oscillation, lack of a strong proof of the mechanism.

The suppression method of the sub-synchronous oscillation of the power system is generally divided into two categories: the change of electrical parameters[7] in power system and the additional damping device[2]. Changing the electrical parameters of the system can inhibit subsynchronous oscillation to a certain extent, but it will limit the economic operation of wind farms and power system. Additional damping devices are divided into series and parallel facilities. The structure of the series device is fixed in the system, and there is the possibility of resonance in the system. If the parameters are not properly adjusted, it may affect the power system in the normal operation state. In contrast, the suppression ability of the parallel type is limited, but the structure is reliable and flexible, and does not affect the normal operation of the system state. Therefore, this paper focuses on improving based on the bypass damping filter[8] to achieve the suppression of subsynchronous oscillation.

In this paper, the system model of doubly fed wind farm is established in Section 2. Then, through the system equivalent circuit, the frequency sweep method is used to analyze the mechanism of the subsynchronous oscillation in Section 3. Finally, a subsynchronous oscillation control strategy based on bypass current compensation is proposed in Section 4. The case study simulated on PSCAD / EMTDC were shown in Section 5. Conclusions were drawn in Section 6.
2 MODEL OF WIND POWER GRID-CONNECTED SYSTEM

2.1 System Structure

In this paper, several models in the same type and running state are used to take the place of actual wind turbines, that is to say that the equivalent of a wind farm is a single large-capacity wind turbine\[9\]. It ignores the interaction between wind turbines, and focuses on the cause analysis of the sub-synchronous oscillation between wind farms and the series transmission lines. Figure 1 is the model of wind power grid-connected system equivalent circuit. It mainly includes wind turbine, induction generator, fan controller, transformer, transmission line and series compensation capacitor. The grid is replaced by an equivalent large power supply.

\[ \begin{align*}
    \text{Wind Turbine} & \quad \text{Induction Generator} \\
    \text{RSC} & \quad \text{GSC} \\
    X_{s1} & \quad X_{s2} \quad R_{s} \quad X_{s} \quad \text{Infinite Bus}
\end{align*} \]

Fig. 1 The equivalent model of wind power grid-connected system

2.2 Wind Turbine

The actual wind turbine is to convert wind energy into mechanical energy. In the establishment of the model, it is to convert wind speed to torque to drive the induction generator. This model ignores the wake effects and other factors. It is well known as a static aerodynamic model. The power \( P \) obtained from wind turbines can be expressed\[10\] as:

\[
P = \frac{1}{2} \rho \pi R^2 V_r^3 C_p
\]

Where \( R \) is the blade radius; \( \rho \) is the air density; \( V_r \) is the wind speed; \( C_p \) is the wind energy utilization factor.

The torque \( T \) of the wind turbine can be expressed as:

\[
T = \frac{P}{\omega} = \frac{1}{2} \frac{\rho \pi R^3 V_r^3 C_p}{\lambda}
\]

\[
\lambda = \frac{\omega R}{V_r}
\]

\[
C_p = 0.518 \left( \frac{116}{\lambda_1} - 0.4 \beta - 5 \right) e^{-12.5 \lambda_1} + 0.0068 \lambda
\]

Where \( \beta \) is the pitch angle and \( \lambda \) is the tip speed ratio.

2.3 Induction Generator

In this paper, the space vector differential equations is used to characterize the model of induction generator. Figure 2 is the model of induction generator equivalent circuit in the dq coordinate system. All variables have been converted to the stator side.

Where \( \omega_s, \omega_r, \xi_s, \xi_r, \Phi_s, \Phi_r \) are stator and rotor voltage, current and flux respectively, ‘s’ on behalf of the stator, ‘r’ on behalf of the rotor. \( R_s \) and \( R_r \) are the stator and rotor resistance; \( L_s \) and \( L_r \) are the stator and rotor inductance; \( L_m \) is mutual inductance; \( \omega_s \) and \( \omega_r \) for the stator and rotor angular frequency.

\[
\begin{align*}
    \frac{d\Phi_s}{dt} &= \omega_s \Phi_s \\
    \frac{d\Phi_r}{dt} &= \omega_r \Phi_r
\end{align*}
\]

Fig. 2 The model of induction generator equivalent circuit in the dq coordinate system

The stator and rotor voltage equations in dq coordinate system are expressed\[11\] as:

\[
\begin{align*}
    u_s &= R_s i_s + \frac{d\Phi_s}{dt} + j\omega_s \Phi_s \\
    u_r &= R_r i_r + \frac{d\Phi_r}{dt} + j\omega_r \Phi_r
\end{align*}
\]

The flux linkage equations are

\[
\begin{align*}
    \Phi_s &= L_s i_s + L_m i_r \\
    \Phi_r &= L_m i_s + L_r i_r
\end{align*}
\]

The relationship between the stator and the rotor angular frequency is

\[
\omega_s + \omega_m = \omega_r
\]

\( \omega_m \) is the slip angle frequency of the motor.

2.4 Controller Model

DFIG uses variable speed and constant frequency control strategy, whose central section is the controller. Figure 3 is the main circuit topology of back-to-back dual PWM converter. The left side connects DFIG rotor used to control the active and reactive power. The middle section is the DC bus regulated capacitor through the right side accessing to the grid. The function of them is to stabilize the DC voltage of the converter at a set value. The controller achieves the maximum power tracking and constant frequency adjustment with variable wind speed.

\[
\begin{align*}
    P_s &= u_{sq} i_{sd} + u_{sq} i_{sd} = u_s \frac{L_m}{L_s} i_{sq} \\
    Q_s &= u_{sq} i_{sd} - u_{sq} i_{sd} = u_s \frac{L_m}{L_s} (\Phi_s + i_{rd})
\end{align*}
\]

Fig. 3 The main circuit topology of back-to-back dual PWM converter
It can be seen from the above formula (6) that the power of the stator side can be decoupled by the vector control in the rotor side. The control block diagram is

![Control Block Diagram]

Fig. 4 RSC control block diagram

3 ANALYSIS OF SUBSYNCHRONOUS OSCILLATION

3.1 Mechanism Analysis

The type of subsynchronous oscillation of the wind turbine is similar to that of the thermal power, which can be both understood as the internal resonance of the power system. Since the natural oscillation frequency of the wind turbine shaft is low, if the shaft resonance occurs, the system must have a very high series compensation. However, the series compensation is too high will cause the voltage drop across the system increases, which is harmful to power system stability. So the wind turbine shaft oscillation is not to happen very often. The cause of subsynchronous oscillation in wind farms is mainly the change of the series compensation.

![Impedance Model]

Fig. 5 The impedance model of wind power grid-connected system diagram

The Fig 5 shows the impedance model of wind power grid-connected system diagram[12]. Seen from the grid side, the system impedance is roughly divided into two parts. The first part is the line impedance: \( X_{\text{line}} \) is the sum of the transformer and the line reactance; \( R_{\text{line}} \) is the line resistance, \( X_{r} \) is the line series compensation capacitor. The second part is the impedance of wind turbine: \( R_{s} \), \( R_{r} \), \( X_{s} \), \( X_{r} \) are stator and rotor resistance; \( X_{T} \), \( X_{m} \) are respectively rotor leakage reactance, stator leakage reactance; \( X_{e} \) is excitation reactance; \( s \) is the slip.

As can be seen from Fig 5, the system equivalent resistance

\[ R_{\text{req}} = R_{\text{line}} + R_{s} + \frac{R_{r}}{s} \]  

(7)

When series compensation capacitor accesses to the power system, the relationship between the system natural oscillation frequency \( f_{n} \) and rated frequency \( f_{0} \) is

\[ \frac{f_{n}}{f_{0}} = \frac{X_{c}}{\sqrt{\sum X}} \]  

(8)

\( \Sigma X \) is the total reactance of the system seen from the grid side.

At the system natural oscillation frequency, the slip is

\[ s = \frac{f_{n} - f_{0}}{f_{n}} = 1 - \frac{\sum X}{X_{c}} \]  

(9)

The magnitude of the series compensation capacitor in transmission line is usually expressed by the series compensation level \( k[13] \).

\[ k = \frac{X_{c}}{X_{\text{line}}} \]  

(10)

\( X_{c} < X_{\text{line}}, k < 1, s < 0 \), under normal circumstances. If \( k \) is increased, \( |s| \) also decreases, but \( \frac{R_{r}}{s} \) increases. When \( k \) increases to a certain extent, \( \frac{R_{r}}{s} < 0 \) and has a large absolute value, then there will be \( R_{\text{req}} < 0 \). At this point, it will lead to continuous current oscillation in power system, which is the phenomenon of subsynchronous oscillation.

3.2 Frequency Scanning

At frequency 50Hz, the wind farm is equivalent to an induction generator. The base value of power plant capacity is 500MVA, and each generator capacity is 2MVA. The equivalent impedance parameters of stator, rotor and transmission line are shown in Table 1. The values of all parameters have been converted to per-unit values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator Resistance ( R_{s} )</td>
<td>0.0161</td>
</tr>
<tr>
<td>Stator Reactance ( X_{s} )</td>
<td>0.2450</td>
</tr>
<tr>
<td>Rotor Resistance ( R_{r} )</td>
<td>0.0165</td>
</tr>
<tr>
<td>Rotor Reactance ( X_{r} )</td>
<td>0.2121</td>
</tr>
<tr>
<td>Transmission Line Resistance ( R_{\text{line}} )</td>
<td>0.0220</td>
</tr>
<tr>
<td>Transformer and Transmission Line Reactance ( X_{T_{\text{line}}} )</td>
<td>0.2100</td>
</tr>
<tr>
<td>Series Compensation Reactance ( X_{e} )</td>
<td>0.0320</td>
</tr>
</tbody>
</table>

The equivalent circuit of system is Fig 5. Seen from the grid side, the system equivalent impedance changes with the frequency \( f_{n} \). Through the frequency scanning method[14], you can get the system equivalent impedance curves at different series compensation levels by changing the system frequency. The conditions of subsynchronous oscillation can be clearly seen from Fig 6.
In Fig 6, the green line represents the system resistance, others are the system reactances. Reactance (20%) is the equivalent reactance when series compensation level is 20%, and others are similar to that. It can be seen from the curves, the system equivalent resistance decreases with increasing frequency, but the equivalent reactance is the opposite. When the line series compensation level is 20%, the resonant frequency of the system is 23.15Hz, and then the corresponding system equivalent resistance is positive, so the subsynchronous oscillation is less likely to occur based on the analysis in section 3.1. As series compensation level increases, the resonant frequency increases, while the corresponding equivalent resistance decreases. When series compensation is 60%, the system equivalent resistance is negative, and then the system is at the risk of occurrence of subsynchronous oscillation.

4 THE SUPPRESSION STRATEGY OF SSO

4.1 Principle of Bypass Damping Filter

The bypass damping filter consists of a resistor R and a parallel LC resonant filter, connected in parallel at both ends of the series compensation capacitor. It is shown in Fig 6. In the case of 50Hz, the bypass damping filter shows high impedance, and the current $i_0$ through it is very small, not affecting the normal operation of the system stability.

The bypass damping filter exhibits low impedance when the subsynchronous frequency current is induced in the circuit. The subsynchronous current $i_{SSO}$ flows through the bypass damping filter, which is equivalent to connecting the resistor R to the system to increase the damping margin of the system, so that the system is in a positive damping state, the current is adjusted to $i_0$, so as to achieve the suppression of the subsynchronous oscillation. However, it cannot achieve a good effect to select frequency by relying on LC parallel resonance only. It is difficult to assess the appropriate value of $R_{BDF}$ to effectively inhibit the subsynchronous oscillation. So it is necessary to improve bypass damping filter.

4.2 Bypass Current Compensation

After the improvement, the passive band-pass filter is used instead of the LC parallel resonance in Fig 7 to achieve frequency selection more accurately. The pass band frequency is also adjusted from 50Hz to the subsynchronous oscillation frequency. The damping section is used to adjust the current amplitude. The phase shifting section is used to adjust the current phase.

The workflow is as follows
1. When the system is running normally, the control system is used to monitor whether the system voltage and current $i_L$ exceeds the rated value, and to judge whether the system occurs subsynchronous oscillation.
2. When the system undergoes subsynchronous oscillation, the current $i_0$ is subjected to Fourier decomposition.

$$i_L = i_{L0} + \sum_{m=1}^{\infty} i_{Lm} \cos(\omega_mt + \phi_m)$$

(11)

The most significant harmonic component $i_{SSO}$ is found by FFT (Fast Fourier Transform) analysis

$$i_S = i_{Lmax} \cos(\omega_{max}t + \phi_{max})$$

(12)

3. The pass band of the band-pass filter is set to $\omega_m$. Then the bypass impedance is reduced, $i_0$, most of the harmonic $i_{SSO}$ flows through the bypass and the other part $i_C$ flows through the series capacitor.

$$i_S = i_0 + i_C$$

(13)

The amplitude and phase of $i_{SSO}$ are adjusted to $i_{B1}$, and

$$i_{B1} = -i_C$$

(14)

Then the harmonic current $i_S$ will quickly reduce, even 0. So the subsynchronous oscillation can be suppressed.

4. Adjust the amplitude and phase of the $i_0$ by adjusting the damping and phase shift sections. The control system can monitor $i_L$ to evaluate the suppression effect, and timely feedback to the bypass. The feedback signals continuously adjust the amplitude and phase of $i_0$. 
The control flow diagram is as follows.

![Control Flow Diagram]

**5 CASE STUDY**

Taking the IEEE first standard model as an example, the model of wind power grid-connected system is shown in Fig. 1, established in PSCAD / EMTDC. The wind farm is replaced by a large single wind turbine with a total power of 500 MVA. The impedance of stator and rotor and electrical parameters of transmission line refer to Table 1.

**Fig. 9 The control flow diagram**

**Fig. 10 The system frequency variation curve**

Fig 10 is the curve of the system frequency. At 1.0s moment, imposing a disturbance to the system, the system frequency began to oscillate. The oscillation of the center frequency is 34.84Hz. It is natural resonant frequency of the system without suppression device in 60% series compensation. Therefore, the center frequency of the band-pass filter is set to 34.84 Hz.

**Fig.11 and Fig. 12 are the system current and active power curve respectively.**

**Fig. 11 The current curve of the system without suppression device**

**Fig. 12 The active power curve of the system without suppression device**

It can be seen from the figure that when the disturbance is added, the system current and active power oscillate. When the disturbance disappears, the amplitude of the active and current oscillations begins to decay. However, they are more severe divergence oscillation later, rather than decay to the steady state before the disturbance. This is because that the disturbance causes the self-oscillation of the system, and if there is no external intervention, the oscillation will become more serious. When subsynchronous oscillation occurs, the system current and active power will oscillate continuously and divergently.

According to the analysis in section 4, the current is subjected to Fourier decomposition. A part of the harmonic current is filtered and phase-shifted through the bypass current compensation device, and then combines with the other part of harmonic in main circuit. It can achieve the goal to eliminate harmonics, thereby suppressing subsynchronous oscillation.

**Fig. 13 and Fig. 14, respectively, are the curves of current and active power in the system with suppression device.**

It can be seen from the figures that when the disturbance disappears in the system with suppression device, the current and active power began to converge after a shock within a period of time. Their amplitude is still fluctuating but in the controllable range. This result shows that the use of bypass current compensation can effectively suppress the subsynchronous oscillation.

**Fig. 13 and Fig. 14, respectively, are the curves of current and active power in the system with suppression device.**

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6 CONCLUSION

The subsynchronous oscillation is a great threat to the safe and stable operation of the power system. In this paper, a simplified model of wind power grid-connected system is established and the mechanism of subsynchronous oscillation is analyzed by frequency scanning method. The frequency-impedance analysis of the model is carried out in the PSCAD / EMTDC. The impedance of the system is related to the frequency and series compensation level. Subsynchronous oscillation occurs in the system when reactance is 0 and resistor is negative. The increase of series compensation level will cause the system resonant frequency to rise.

In the case of suppression, the bypass damping filter has been improved. The RLC parallel resonance damping filter is replaced by band-pass frequency selection, damping and phase shift control. The control mechanism is also changed from the damping suppression into the bypass current compensation. The experimental results show that the method can suppress the subsynchronous oscillation to a certain extent. The device does not affect the normal operation of the system because it accesses only in the system failure.

As the device designed needs to be connected in parallel on the high voltage side, the components need to withstand high voltage and high current. So the current research on the bypass current compensation is still in the theoretical research stage. In the future will be further study in the feasibility of engineering applications.

REFERENCES
