Studies of Sub-Synchronous Oscillations in Large-Scale Wind Farm Integrated System

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Abstract. With the rapid development and construction of large-scale wind farms and grid-connected operation, the series compensation wind power AC transmission is gradually becoming the main way of power usage and improvement of wind power availability and grid stability, but the integration of wind farm will change the SSO (Sub-Synchronous oscillation) damping characteristics of synchronous generator system. Regarding the above SSO problem caused by integration of large-scale wind farms, this paper focusing on doubly fed induction generator (DFIG) based wind farms, aim to summarize the SSO mechanism in large-scale wind power integrated system with series compensation, which can be classified as three types: sub-synchronous control interaction (SSCI), sub-synchronous torsional interaction (SSTI), sub-synchronous resonance (SSR). Then, SSO modelling and analysis methods are categorized and compared by its applicable areas. Furthermore, this paper summarizes the suppression measures of actual SSO projects based on different control objectives. Finally, the research prospect on this field is explored.

Keywords. series compensation; Sub-Synchronous oscillation; analysis method; suppression measures.

1. Introduction

Large-scale development and utilization of wind energy has become an important part of China's energy strategy. Due to the reverse distribution of wind energy resources and load center, large capacity and long distance wind power transmission is imperative, the high voltage series compensation and HVDC (High Voltage Direct Current) technology has been widely used to achieve the long distance transmission capability, but the use of series compensation and HVDC transmission mode may cause sub-synchronous oscillation (SSO), and influence the safety and stability of wind farms and grid. According to the interaction of different mechanism in large-scale wind power integrated system, the SSO problems can be classified into the following broad categories [5-10]:

Sub-synchronous control interaction (SSCI), relates to the interaction between the series compensated transmission grid and the control systems associated with a DFIG-based wind turbine. As

evident from the aforementioned definition, unlike TI (Torque Interaction, TI) or TA (Torque Amplification, TA), SSCI is a purely electrical phenomenon.

Sub-synchronous torsional interaction (SSTI), relates to the interaction between wind turbine controller or adjacent FACTS device controller and the generator turbine-shaft system.

Sub-synchronous resonance (SSR): This phenomenon corresponds to the traditional concern associated with the resonance between the mechanical characteristics of the generator turbine-shaft system and the electrical characteristics of the series-compensated grid. The phenomenon of SSR has been observed to manifest itself in the form of torsional interaction (TI), induction generator effect (IGE), or torque amplification (TA).

One unstable SSO event occurred in Zorillo area of southeast Texas on Oct.22, 2009.The event revealed the fact that wind turbine generators (WTG) can be susceptible to SSO problem when it is connected to the grid via series compensated (75%) transmission lines [11].Then, the ERCOT (Electric Reliability Council of Texas) requires all newly proposed project studies about SSO problems caused by wind farms integrate to grid. Then taking northern China region for example, the SSO problems caused by DFIG-based wind farms integrated to grid by series compensation has repeatedly appeared since 2011 [12-14].

In the context of the discussion presented in this paper, there are a variety of wind turbine and reactive power compensation device in control parameters and operation mode, so the inducement mechanism, related characteristics, suppression categories and analysis methods for different SSO types are different from each other. This paper first introduces the SSO's mechanism of large-scale wind farm by series compensation, exchange system or HVDC grid-connected. Then, systematically summarize the analyzing method of sub-synchronous oscillation in large-scale wind farm integrated into power system. By organically combining this method and SSO's mechanism, the suppression strategy of SSO has been summarized. Finally, the future research direction and focus of SSO in large-scale wind farm integrated into grid are discussed.

2. The Sypes and Mechanism For Wind Farm SSO Problems
After the SSO problems had occurred two times in Mohave power plants due to the series of cable transmission caused by shaft torsional vibration accident, the academic community and industry has paid great attention to the mechanism and suppression method of SSO problems which caused by wind farms integrated into grid. Simultaneously, a

Lot of research results and papers has been presented,   according to the published literature and interaction mechanism, the problem of synchronous oscillation in large-scale wind farm grid-connected system can be divided into three types: SSR, SSCI, and SSTI. Fig.1 shows the classification of SSO in DFIG-based wind farms.
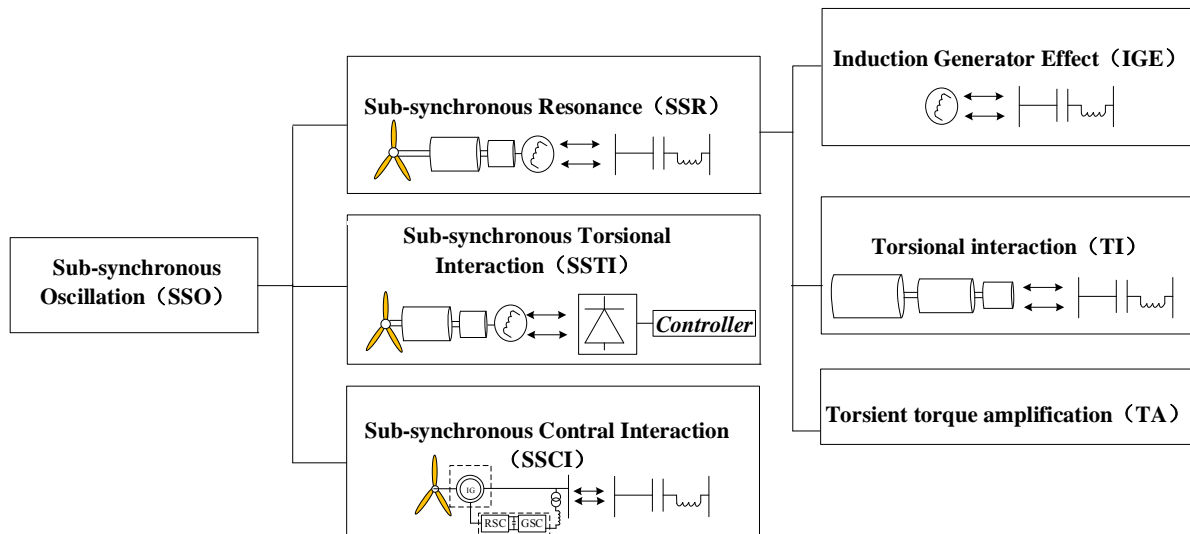
Fig.1 Classification of sub-synchronous Oscillation (SSO) of DFIG-based wind farm

2.1. Sub-synchronous resonance

As is shown in Fig.1, the sub-synchronous resonance circuit can be conformed between the compensation capacitor in series compensation and the stator inductance of wind turbine shaft, and the energy is exchanged between the wind turbine and electric network with one or more sub-synchronous frequency, which endangers the safety and stability of wind turbine and power system [15-18]. The SSR is divided into steady SSR and transient SSR, the steady SSR includes induction generator effect (IGE), torsional interaction (TI), and transient SSR includes torque amplification (TA).As shown in figure 1, TI and TA result from the interaction between generator shaft and the series compensated line, only exist when the shaft torsional oscillation frequency and the resonant frequency of series compensated line are complementary for power frequency. Due to the natural torsional vibration frequency of DFIG wind turbine shaft is too low, and the corresponding complementary frequency is too high, so that requires a high series compensation level. So, the phenomenon of TA and TI in DFIG-based wind farms is too hard to be triggered in normal wind farm system parameters. As a result, researchers and engineers focus more attention on the IGE in DFIG-based wind farms.

IGE is a pure electric self-excited oscillation phenomenon, and has nothing to do with the mechanical system [19-21]. Fig.2 shows the structure diagram of series compensation system, where R_L, X_L and X_C are respectively equivalent resistance, reactance and capacitor reactance of transmission line. X_T, X_{SYS} and R_{SYS} are respectively transformer, equivalent resistance and reactance of infinite bus system.
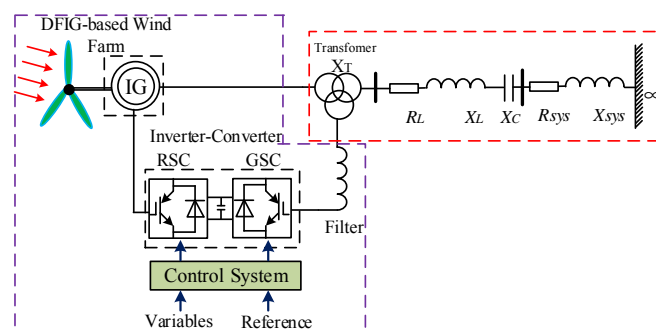

Fig.2 Structure diagram of the series compensation system with DFIG-based wind farm

Where the wind turbine generator's rotor in sub-synchronous frequency (f_{er}) can be expressed as:

$$S_{er} = \frac{f_{er} - f_r}{f_{er}} \times 100\%$$

(1)

In the equation (1), f_r is the rotor frequency, by setting $f_r = (1 - s_0)f_1$, s0 is the initial rotor slip rate. f_r Can be assumed as a constant number for f_1 is almost unchanged during the short oscillation period. Regardless of the influence of the rotor-side inverter, the power system equivalent circuit of IGE is shown in Fig.3.Generally, $S_{er} < 0$, so the rotor equivalent resistance of DFIG (Rr/Ser<0)

Is negative, where the absolute value of Rr/Ser can be expressed as equitation (2):

$$\frac{R_r}{|S_{er}|} = \frac{R_r}{|1 - f_r / f_{er}|} = \frac{R_r}{f_r / f_{er} - 1}$$
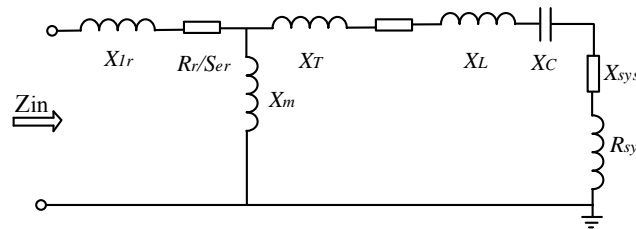
(2)

Fig.3 the equivalent circuit used for IGE analysis

The conclusion can be concluded from equitation (2) and Fig.3, when the absolute value of the equivalent resistance is bigger than the sum of transmission systemic resistance and stator resistance, the equivalent resistance of the whole power system is native in sub-synchronous frequency, so that lead the transmission current in a continuous oscillation, and that is so-called the IGE.

Under normal condition, the SSR is the dominant form of the oscillation type [22-24]. Reference [25-26] presents a case study associated with the influencing factors and mechanism of IGE that occurred in a grid-integrated wind energy conversion system (WECS), and find that increasing series compensation level will induce the phenomenon of IGE. Reference [27] presents a comprehensive approach for SSR by developed frequency-scan tool, and indicate that wind speed, series compensation level, integrated-grid number and the control mode are the dominant factors of SSR. Reference [28] designs a equivalent model of wind farms integrate into AC power system via series compensation, the simulation results reveal the phenomenon of SSR can be occurred when satisfying certain conditions. Meanwhile, the eigenvalue analysis is applied to small signal stability of the system, the analysis results indicate the SSR mechanism.

2.2. Sub-synchronous torsional interaction
The structure diagram of sub-synchronous torsional interactions is shown as Fig.1. A second cause of concern with regard to torsional modes is that of sub-synchronous torsional interactions (SSTI) for the controller parameters or operation modes of other transmission equipment such as HVDC or static var compensator (SVC) are unreasonable. The dynamic var compensation is well-known equipment that can improve the transient stability and support the voltage and reactive power for grid. The modular multilevel HVDC converters (MMC) is broadly used as its flexible active and reactive decoupling control. However, the rapid response capability of these power electronic devices may induce and aggravate the risk of SSTI.

Reference [29] presents an analytical study for examining SSTI between FACTS controller, load characteristics and turbo-generators in a large-scale power system. Reference [30-32] indicates potential SSTI concerns that the rapid response of power electronics equipment controller may make a negative

influence on phase-difference between electromagnetic torque and rotor speed of wind generators, the wind generators will be in a negative damping situation and risk in system's sub-synchronous oscillation once the phase-difference greater than 90°. Reference [33-34] focus on the SSTI problem which is the wind farm integrate into grid by VSC-HVDC, and designs an effective suppression strategy for damping control of VSC and wind controller, and simulation results reveal that the real mechanism of oscillation in HVDC-contacted system is the interaction between HVDC system and converter.

2.3. Sub-synchronous control interaction
Completely different from the traditional oscillation, SSCI has nothing to do with wind turbine shaft, and a lot of research has demonstrated the interaction between series compensations and wind turbine controllers is the main induced factor. Reference [35] presents a comprehensive approach for the character of SSCI, and reveals the important phenomenon that the increasing of compensation level and RSC-side current controller's parameters, decreasing of wind speed can lead to the risk of SSCI. Reference [36] design a simulation model for SSCI, and indicates the main mechanism of SSCI is that DFIG-based generator has a negative resistance at sub-synchronous frequency. Because of fault or disturbance in power system, the stator current may contain resonant component *is* (*fer*), meanwhile, the rotor side will induce current component *ir* (*fr-fer*) and the rotor voltage will arise component *ur* (*fr-fer*),Which will in turn act on the rotor current and finally affect the stator current. If positive feedback is formed, the sub-synchronous component of stator current will increase gradually, which can occur the phenomenon of oscillation.

3. The Analysis Method For SSO
At present, there are many analysis methods for analyzing the synchronous oscillations problems of DFIG-based wind farms. Several typical and effective analysis methods are: frequency scanning method, complex torque coefficient method, eigenvalue analysis method, time domain simulation analysis. However, different analysis method have their own suitable area, advantages and disadvantages.

3.1. Frequency scanning method
The frequency scanning is a rough and fundamental method for judging the possibility of SSO in the system, meanwhile, this method can be used for linearizing the operating characteristics of the nonlinear device near an operating point and analyzing its response. Reference [37] presents the main procedure about this method: (1) Establishing the positive negative network of WECS; (2) Calculating the WG-side state equivalent impedance of other grid components (including wind turbines, lines, transformer, etc.); (3) Then calculate and obtain the curve of SSO equivalent reactance and resistance with the frequency variation. When the SSO equivalent resistance satisfy the equation (3), the power system will be in the risk of SSO, and the oscillation amplitude will be greater with the absolute value of equivalent resistance increasing.

$$\begin{cases} R_{eq\_sso}\big|_{f_{er}} < 0 \\ X_{eq\_sso} = 0 \end{cases} \tag{3}$$

3.2. Eigenvalue analysis method
Eigenvalue analysis method is also called mode analysis method, the method can be summarized two parts. Firstly, a small disturbance signal is added to WECS. Then, establishing the linearized model for calculating the eigenvalues, eigenvectors and correlation factors of system state matrix. The equation (4) is the nearly linear state matrix:

$$\Delta \dot{X}_{sso} = A_{sso} \Delta X_{sso} \tag{4}$$

Then, calculate the eigenvalue λ_n of coefficient matrix *Asso*:

$$\lambda_n = \sigma_n + j2\pi f_n \tag{5}$$

As is shown in equation (5), σ_n and f_n are respectively eigenvalue real part and mode frequency of SSO. Finally, the system's stability can be judged by the distribution of the eigenvalues on complex plane, when the characteristic roots are distributed in left half plane, the oscillation will be weaken or doesn't occur in sub-synchronous frequency, and the damping coefficient is proportional to the absolute value of latent root's real part. On the contrary, when the latent root is located on the imaginary axis or the right half plane of the complex plane, the corresponding oscillation mode will be unstable in sub-synchronous frequency. Reference [38-39] established the equivalent model of DFIG-based wind farms connected to a series-compensated power system, and analyze the variation of different factors influence the wind turbine's stability and reliable operation area by eigenvalue analysis method. The comprehensive simulation results reveal that the larger the compensation level and the proportion of current loop of rotor-side converter, the smaller the stable area.

This method can be applied for the problems of SSCI and SSTI, but not suitable for complex highly nonlinear system. However, it has a strong scientific theory, a accurate analytical method. It can be used to optimize the design controller to suppress the SSO and analyze the various SSO problems besides SSR. Meanwhile, it can only be applied to describe the system by positive sequence network. Obviously, the system state matrix dimension will be constraint by the problem of curse of dimensionality".

3.3. Complex torque coefficient method
Complex torque coefficient method can be considered as the combination of eigenvalue analysis method and frequency scanning method. This method is to apply a forced small amplitude oscillation $\Delta\delta$ at a relative angle (δ) of a generator rotor in system:

$$\begin{cases} \Delta\delta = \Delta\delta_m e^{j\zeta t} \\ \zeta = 2\pi f \end{cases} \tag{6}$$

$\Delta\delta_m$ Is the amplitude of oscillation. The equivalent electrical and mechanical complex torque coefficient can be defined as equation (7). Among them, ΔT_M and ΔT_e is respectively the increment of mechanical and electrical complex torque because of small amplitude oscillation.

$$\begin{cases} K_E(j\zeta) = \Delta T_e / \Delta\delta \\ K_M(j\zeta) = \Delta T_M / \Delta\delta \end{cases} \tag{7}$$

Usually, $K_E(j\zeta)$ and $K_M(j\zeta)$ are complex number, so $K_E(j\zeta)$ and $K_M(j\zeta)$ can be performed as equation (8).

$$\begin{cases} K_E(j\zeta) = K_e(\zeta) + j\zeta D_e(\zeta) \\ K_M(j\zeta) = K_m(\zeta) + j\zeta D_m(\zeta) \end{cases} \tag{8}$$

$K_e(\zeta), D_e(\zeta)$ and $K_m(\zeta), D_m(\zeta)$ are respectively the elastic coefficient and damping coefficient of electric and mechanical system. The discriminant equation as is shown in equation (9) can be judged the system is in unstable oscillation condition.

$$\left\{ D_m(\zeta) + D_e(\zeta) \right\}_{K_m(\zeta)+K_e(\zeta)=0} < 0 \tag{9}$$

This method can be applied to actual engineering project such as "Research on SSR Characteristics of Ximeng-Shandong UHV AC Series Compensated Transmission system" for its fundamental theory which is based on system linearization, and overcome the problem of "curse of dimensionality".

4. Suppression Strategy for SSO

Since the emergence of SSO, domestic and foreign scholars have studied the suppression strategy. According to the corresponding SSO mechanism, the IGE generally don't cause a serious accident. As for SSCI, the analysis of mechanism is less, and there is no uniform conclusion in academic areas. IGE will be occurred when the series compensation level increase, the wind generators capacity increase or wind speed decrease. Meanwhile, SSCI will be excited in the condition of RSC-side parameters in current loop is unreasonable [40-41]. The suppression strategy can be divided into three categories, as is shown in Fig.3.
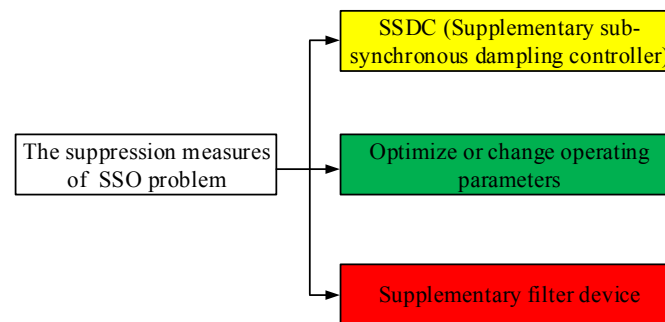

Fig.4 The classification of SSO suppression measures

4.1. SSDC measures

The SSDC measures can be divided into two direction. The first supplementary measure is adding damping controller in RSC-side or GSC-side controller, the engineering projects have witnessed the oscillation can be suppressed. Reference [42] analyse the wind speed, gain of inner loop, series compensation level and integral time constant of controller can decrease or increase the electric damping, and the simulation results reveal that proportional and integral parameters has little effect on the damping characteristics of DFIG-based wind generator, meanwhile, this paper presents a suppression strategy for which is adding H-SSDC (Hybrid Sub-Synchronous Damping Controller) in the rotor side converter of DFIG, and the effectiveness of restraining SSCI is verified by the simulative results.
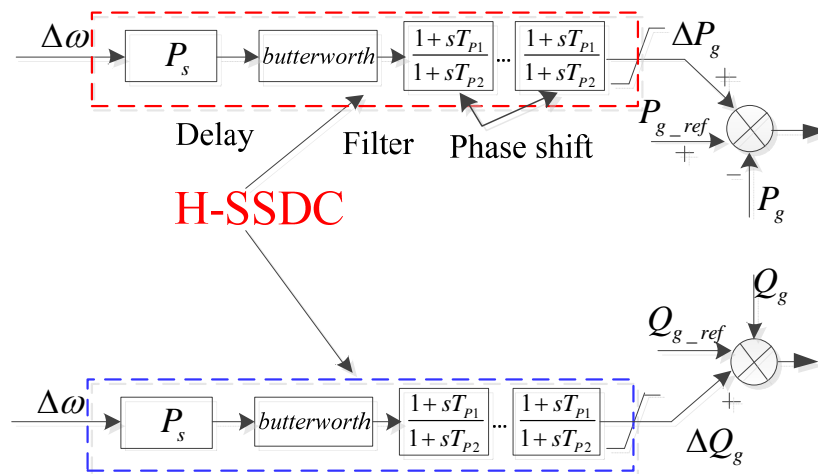
Fig.5 Structure diagram of H-SSDC measure

The suppression strategy of SSO problems is adding SSDC of parallel FACTS devices such as: SVC (Static Var Compensator), STATCOM (Static Synchronous Compensator), UPFC (Unified Power Flow Controller), et al. Reference [43] presents a SSC (Sub-Synchronous damper) which can suppress the SSO problems occurred by wind farms VSC-integrated system. Time domain simulation results have verified the effectiveness of supporting positive damping for SSCI system. Damping sub-synchronous oscillation using static VAR compensators (SVC) is investigated in the reference [44-45], and in order to damp the various unstable torsional modes, a sub-synchronous damping controller is designed according to the phase compensation methods. Eigenvalue analysis of the closed-loop system and test signal method reveal that this controller is effective. The time domain simulations are also performed to demonstrate the e ectiveness of the proposed controller under disturbance condition, the results show that the SVC used in Hulun Buir power plant can mitigate the SSO phenomenon.

4.2. Optimizing the operating parameters
Optimizing the operating parameters can be divided into the following parts:

Optimizing the controller parameters of wind generator. By changing the parameters of the controller, improving the control strategy, improving the stable ability of the wind turbine to suppress the SSO problems, changing the output impedance characteristic of the wind turbine so that changing the SSO's resonance point of the interaction between the wind turbine and grid, it can effectively reduce the risk of SSO problem to the safe and stable operation of the hazards. Reference [46] presents an idea that reducing the risk of the SSO problem of grid-connected system of wind farms by optimizing the control parameters of the current loop and phase-locked loop of the wind turbine converter.

Series FACTS device. The series-type FACTS devices, which are commonly used to suppress the sub-synchronous oscillation of wind power system, mainly include thermistor controlled series capacitor (TCSC), gate-series control series capacitor (GCSC), static synchronous series compensator (SSSC), etc. Reference [47] analyze the comprehensive suppression measures about TCSC and GCSC, and the damping effect of SSCI under large interference is verified by simulation. Although the FACTS device can achieve a good suppression effect by reasonable design, it is connected in series to the system, which is not flexible enough and lacks reliability, and the full control type FACTS device is expensive.

Changing the system operation mode. In the actual operation of the wind farm grid-connected system, if the SSO problems has been detected in the system, changing the operation mode can avoid the further expansion of the accident, such as cutting reactive power compensation equipment, SVG constant voltage control to constant Power control, wind farm or HVDC down power operation, removal of wind turbines, etc.

4.3. Additional filtering device

Bypass damping filter (BDF) and block filter (BF) is the usual filtering device in suppressing the SSO problems. BDF is connected in series with a resistor and a plurality of LC parallel resonant filters in series. Under normal operating conditions, BDF has high impedance at power frequency and low impedance at sub-synchronous frequency, so the frequency current in the filter is very small and the sub-synchronous current is very large, so that the occurrence of sub-synchronous oscillation can be mitigated. Corresponding to BF, it can block the interaction between wind turbine mechanical system and the grid electrical system, which can inhibit the generation of sub-synchronous oscillation [4, 48].

5. Conclusion

Firstly, this paper discusses the different sub-synchronous oscillation categories and its mechanism of DFIG-based wind farm integrated system. Then summarize the analysis method and compare the corresponding pros and cons according to the different interaction mechanism. Finally, this paper summarizes the suppression measures of actual SSO projects. However, the future areas of the sub-synchronous oscillation will continue to deepen such as mechanism, suppression measures, characters of SSO. The following is the further work which is underway with respect to development.

Considering the technical and economic factors, there are many potential suppression measures are not realized. The IGE problems can be solved by installing the damping winding in rotor circuit; the double-gap capacitor flashover and additional excitation damping control can be effectively applied to suppress the sub-synchronous resonance caused by the interaction between transient torque and the electromechanical torque, and the three kinds of suppression measures are relatively inexpensive and have good prospect.

Heterogeneous multi-machine Simultaneous Oscillation problem of large-scale wind power grid-connected System. The existing research on the problem of grid-connected wind farm system is mostly based on the stand-alone infinity system. The multi-machine system only considers the same control parameters and the same type of wind turbine, and does not consider the different types of wind turbine interaction. The corresponding suppression measures also do not take the variation of wind turbine parameters and controller parameters into consideration.

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