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Research on Sub-synchronous Oscillation Characteristics between PMSG-based Wind Farms and Weak AC Grids Based on Prony Method

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***Abstract*—To investigate the new type of sub-synchronous oscillation (SSO) incidents in permanent magnet synchronous generators (PMSG) based wind farm in Xinjiang grids, this paper establishes an equivalent grid model based on practical Xinjiang grids data in PSCAD/EMTDC. To avoid the complexity and limitations of eigenvalue analysis, the Prony method is adopted to obtain system damping information. Then, taking one of those wind farms as a research case, the impacts of main factors on SSO characteristics are discussed in detail. The analysis of results reveal that improper operating conditions would weak the sub-synchronous damping and stimulate SSO in wind farm. Additionaly, a possible safe operation range of one PMSG-based wind farm through extensive simulations is presented in this research work. To further extend the solution of exsiting problems, an additional mitigation strategy based on static synchronous series compensator (SSSC) is introduced to compensate the sub-synchronous voltage and thus to suppress the SSO.**

Keywords—sub-synchronous oscillation, permanent magnetic synchronous generators, wind farm, weak girds, Prony, mitigation

I. INTRODUCTION

As a fast developing and widely concentrated renewable energy, wind power accounts for a growing proportion of generating capacity in power system due to significant advantages. However, the increasing scale of wind farm brings some new challenges to power system. As one of them, a new sub-synchronous oscillation (SSO) problem caused by the interaction between the wind farm and the AC grid has received abroad attention [1].

In October 2009, a sub-synchronous oscillation accident occurred in southern Texas, resulting in the trip of numerous wind turbine generators (WTGs) and damages to some system components. A similar accident occurred in Guyuan of China in December 2012. Both of them took place where the doubly-fed induction generator (DFIG) wind farms are connected to the grid via series-compensated transmissions lines. The main cause is the sub-synchronous control interaction (SSCI) between the series compensation capacitor and the wind farms.

As another type of variable speed wind turbine generators, permanent magnet synchronous generators (PMSG) have crucial advantages, especially for high reliability. Besides, some researchers have declared that there is no SSCI problem between PMSG wind farm and AC grids. Reference [2]-[3] presented that the WTG has no direct coupling with fixed series compensation capacitor and the resonant current fails to enter into wind generator due to converter's separation. Moreover, those views have been confirmed to some extent by several simulations. While in July 2015, a new type of SSO incident caused by PMSG-based wind farms happened in Xinjiang province of China. The oscillating current flowed around, in this accident, causing the torsional protection system startup and the trip of nearby thermal turbine generators [6]. Unlike the aforementioned incidents, This happened between PMSG-based wind farms and weak AC grids without series compensation, which cannot be explained by previous studies. Therefore, it's necessary to find out its mechanism and characteristic.

There is some research on the SSO between PMSG-based wind farms and weak AC grids. Based on eigenvalue analysis, the authors of [7]-[8] studied the SSO mechanism in PMSG-based wind farm, which is equivalent to a single wind turbine. Besides, the impact of controller parameters of SVC on SSO in PMSG-based farms is analyzed in [9]-[10]. Harmonic stability and resonance analysis in large PMSG-based wind power plants was carried out [14]. However, the author focused on the system's stability at high frequencies rather than sub-synchronous frequencies. To study the harmonic stability of voltage source converters and PMSG-based wind farms, [12]-[15] deduce the equivalent impedance or admittance model under the *d-q* reference frame.

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While most of those studies are based on one single PMSG or simplified wind farm, their general works are hard to depict SSO characteristic of PMSG-based farms specifically in practical Xinjiang grids. At present, for Xinjiang grids, the primary responses against the SSO incidents caused by PMSGs are still cutting out those WTGs directly when SSO is detected. Nonetheless, monitoring gaps may exist, especially when the sub-synchronous harmonic amplitude is small. This could result in sub-synchronous harmonic diffusion in the grid. Therefore, it's essential to investigate the SSO characteristic of PMSG farms based on practical Xinjiang grids and design an effective mitigation strategy.

This paper analyzes the SSO characteristic of PMSG-based farms in Xinjiang grids. The contributions of this work are as follows: 1) An equivalent model based on the Xinjiang Hami grids data for SSO analysis is built in PSCAD/EMTDC. 2) The influence of mainly potential factors, including AC grid strength, wind speed, number of grid-connected WTGs and parameters of controller, on oscillation and damping characteristic of PMSG-based wind farms are analyzed by Prony methods. 3) A possible safe operation range of PMSG-based wind farm is put forward. 4) A feasible SSO mitigation method based on static synchronous series compensator (SSSC) is introduced.

Rest of paper is organized as follows: Section II introduces the simplified PMSG-based wind farm model and equivalent Hami grids model. Section III analyses the impact of main factors on SSO characteristic of PMSG wind farms by time-domain simulation and Prony analysis. Then, a possible safe operation range of a PMSG-based wind farm is provided. Section IV introduces a feasible SSO mitigation method based on SSSC. Finally, conclusions are drawn in Section V.

II. Description of System Model

A. *PMSG-based Wind Model*

Reference [13] emphasizes the inner loop of the power

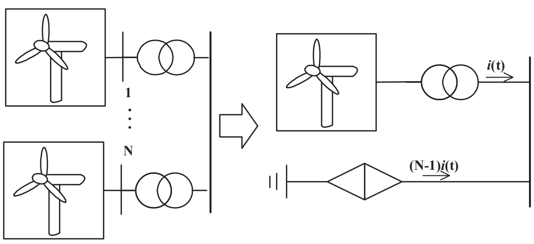


Fig. 1. Wind farm equivalent Schematic

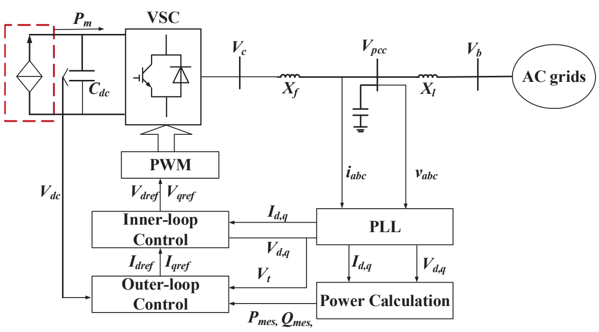


Fig. 2. Schematic of simplified PMSG

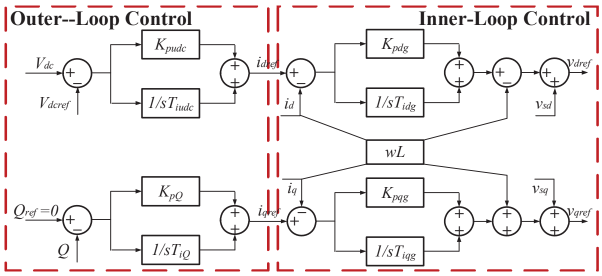


Fig. 3. Control block diagram of GSC

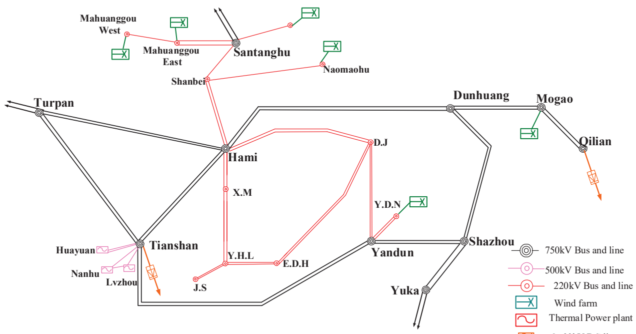


Fig. 4. Schematic of equivalent Xinjiang grids.

TABLE I. Model Composition and Statistics

Main parts	**Model Statistics**	
	Number	***Name***
Substation (750kV)	10	Hami, Tianshan, Turpan, Santanghu, Yandun, Shazhou, Mogao, Qilian, Dunhuang, Yuka
Substation (220kV)	7	Shanbei, Xingmin,Yinhelu, Jinsheng Meiye, Dongjiang,Erdaohu, Yandunnan
Wind farms	6	Mahuanggou East, Mahuanggou West, Datang Hongxing, Shanbei Station, Mogao Station
Thermal power plant	8	Huayuan, Nanhu, Lvzhou
HVDC	2	Ha Zheng, Jiuhu

electronic equipment which generally adopts current control, and cannot work normally when the external circuit is open. Therefore, the power electronic equipment is always equivalent to current source shunt with impedance. Meanwhile, in order to facilitate the analysis,it is assumed that all PMSGs in the same wind farm share identical parameters and operating conditions. Thus, the wind farm is equivalent to one PMSG machine shunt with current source, as shown in Fig. 1. The rated capacity of one PMSG is 5 MW.

Furthermore, the Hami grid model contains 6 PMSG-based wind farms. On the premise of guarranteeing the simulation precision, the machine side of PMSG is equivalent to a controlled current source, as shown in Fig. 2. The current reference value is obtained by dividing the power reference P_{ref} given by Maximum Power Point Tracking (MPPT) module by the DC voltage V_{dc} of the capacitor.

Generally, the on-grid dynamics of a PMSG are mainly affected by the control features of its grid-side converter (GSC), which is illustrated in Fig. 3, where V_{dcref} is the reference voltage of DC capacitor, Vdc is the actual voltage of DC capacitor, K_{pudc}, T_{iudc}, K_{pQ}, T_{iQ} are the control parameters of voltage outer-loop of GSC, K_{pdg}, T_{idg}, K_{pqg}, T_{iqg} are the control parameters of current inner-loop of GSC.

B. The Equivalent Xinjiang Grids

Taking Santanghu, Turpan, Qilian and Yuka substations (750kV) as the boundary of the equivalent model and retaining the 750kV grids along with partial 220kV grids, the equivalent Xinjiang grids are illustrated in Fig. 4.

The main parts of equivalent Xinjiang grids are listed in Table I. Besides those, the rest substations are equivalent to load.

III. Research of SSO Characteristics of PMSG-based Wind Farm in Xinjiang Grids

A. Prony Method

The methods of studying SSO are mainly divided into two categories. Both are time-domain analysis and frequency-domain respectively. The former refers to eigenvalue analysis is used for a small case study. Given the scale and complexity of Xinjiang grids model, the time-domain analysis (electromagnetic transient analysis) combined with Prony method is adopted.

Similar to the Fourier transform, Prony's method extracts valuable information from a uniformly sampled signal and builds a series of damped complex exponentials or sinusoids. Specifically, it is assumed that f (t) is a signal consisting of N evenly spaced samples. Prony's method fits a function to the observed f (t), which satisfies

$$\begin{aligned}\hat{f}(t) &= \sum_{i=1}^{M} A_i e^{\sigma_i t}\cos\left(2\pi f_i t + \phi_i\right) \\ &= \sum_{i=1}^{M} \frac{1}{2} A_i e^{\pm j\phi_i} e^{\lambda_i t}\end{aligned} \tag{1}$$

Where the M is the number of order, A_i are the amplitude components of the series, σ_i are the damping components, f_i are the frequency components, ϕ_i are the phase components, and $\lambda_i = \sigma_i \pm j\omega_i$ are the eigenvalues of the system.

B. The Influence of Main Factors on SSO Characteristics

1) The AC grids strength

To analyze the strength of AC network, the concept of short circuit ratio (SCR) in HVDC is introduced. Its definition is

$$SCR = \frac{S_{ac}}{P_{wind}} \tag{2}$$

Where the S_{ac} denotes the short circuit capacity of AC network, P_{wind} is the capacity of wind farm.

Taking the Mahuanggou West wind farm as a study case in this paper, the capacity of the wind farm is 300MW. The initial simulation conditions are: number of grid-connected WTGs (N_{WTG}) =30, SCR=3.5, wind speed (V_w) = 12m/s (rated speed). At 2.4s, SCR decreases to 1.35 suddenly and lasts until the end. we record variations of the phase-A line current, the active power of wind farm and make Fast Fourier Transform (FFT) and Prony analysis of the line current aiming to extract key information of SSO. The result is illustrated in Fig. 6. Obviously, both the current and power signal diverge at once when the SCR decreases at 2.4s. after a short time, both enter sustainable oscillation approximately. According to FFT results of phase-A current, undoubtedly, the current contains sub-synchronous (21.48Hz) and 121.6Hz components. Furthermore, the sub-synchronous damping negative based on Prony analysis is calculated. Up to a point, this reveals the possible mechanism of SSO in PMSG-based farms.

To investigate the relationship between SCR and SSO, we make a series of simulations. We reduce SCR from 3.5 to 1.5 and only focus on the sub-synchronous damping. The final Prony results are shown in Table II and Fig. 5. Note, the real part of the eigenvalue indicates damping property and the imaginary part refers to oscillatory angular frequency. Obviously, the decrease of SCR, namely the weakening of

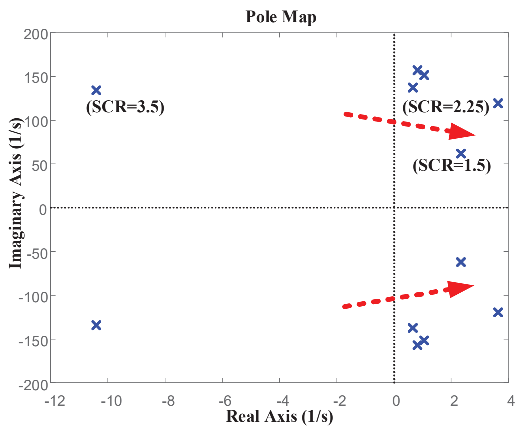


Fig. 5. The eigenvalue identified by Prony method when SCR decreases from 3.5 to 1.5.

TABLE II. PRONY RESULTS STATISTICS

SCR	Prony results of Ia		
	Frequency of SSO (Hz)	*Damping* (1/s)	*Amplitude* (%)
3.5	21.42	0.0773	0
3	25.01	-0.00521	0.4
2.5	24.12	-0.00695	3.7
2.25	21.85	-0.0048	4.1
2	19.03	-0.0304	5.2
1.5	9.88	-0.0377	10

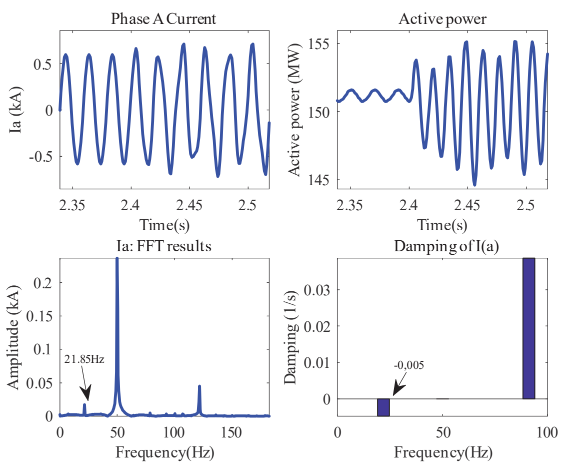


Fig. 6. The response of current and active power when SCR decreases from 3.5 to 1.5.

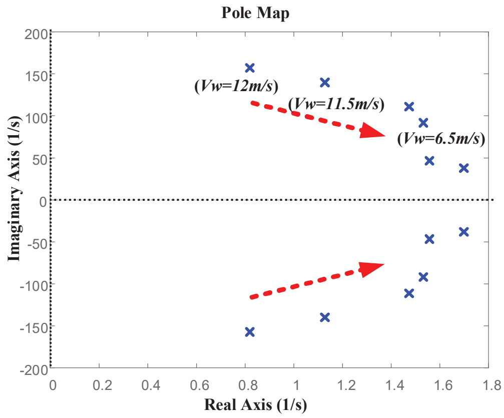


Fig. 7. The eigenvalue identified by Prony method when V_w decreases from 12 m/s to 4.5 m/s.

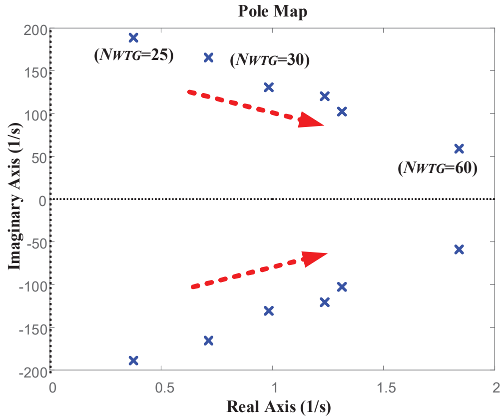


Fig. 8. The eigenvalue identified by Prony method when N_{WTG} increases from 25 to 60.

TABLE III. PRONY RESULTS STATISTICS

V_w(m/s)	Prony results of Ia		
	Frequency of SSO (Hz)	*Damping* (1/s)	*Amplitude* (%)
12	25.010	-0.005	0.4
11.5	22.241	-0.008	5
10	17.692	-0.013	8.6
9	14.612	-0.017	16.2
6	7.424	-0.033	27.2
4.5	6.046	-0.045	32.6

TABLE IV. PRONY RESULTS STATISTICS

N_{WTG}	Prony results of Ia		
	Frequency of SSO (Hz)	*Damping* (1/s)	*Amplitude* (%)
25	30.040	-0.002	2.8
30	26.320	-0.004	4.7
40	20.811	-0.008	7.4
45	19.161	-0.010	11.3
50	16.301	-0.013	15.8
60	9.375	-0.031	53

AC grids, have significant impacts on SSO. With the decrease of SCR, the sub-synchronous damping varies from positive to negative as shown in Fig. 6. Specifically, when SCR is less than 3, the SSO incident will happen. Furthermore, with the decrease of SCR, the SSO frequency changes similarly. However, as the relative percentage of

fundamental frequency component, the amplitude of sub-synchronous current varies in the opposite way.

2) The wind speed

Generally, the MPPT strategy is adopted in wind farm. Below rated wind speed, the output power of WTG is approximately proportional to the three squares of wind speed. In other words, as the wind speed decreases, the output power decreases.

The initial simulation conditions are: N_{WTG}=35, SCR=3, V_w =12m/s. To find the relationship between V_w and SSO, we carry out a series of simulations by reducing the Vw from 12m/s to 4.5m/s. During the simulation, similarly, we record

the phase-A current and analyze it by Prony method. Fig. 7 and Table IV depict the changes of SSO with the decrease of V_w. Clearly, the decrease of wind speed could worsen the sub-synchronous damping, which increases the risk of SSO incident. Meanwhile, with the decrease of wind speed, the SSO frequency changes similarly.

3) The number of grid-connected WTGs

The increase of number of grid-connected WTGs means the increase of the scale of wind farm. The SCR, according to the aforementioned definition, is inversely proportional to the scale of wind farm. Hence, with the continuous construction of wind farm, the risk of SSO could increase. To verify that, we run a series of simulations by increasing number of grid-connected WTGs gradually.

The initial simulation conditions are: N_{WTG} =10, SCR=2.25, V_w=12m/s. Then we change the value of N_{WTG} from 25 to 60 and the variations of the SSO-related eigenvalues are depicted in Fig. 8 and Table III.

The results indicate the increase of NWTG diminish sub-synchronous damping and increase SSO risk. Besides, the sub-synchronous frequency decreases along with increase of N_{WTG}.

4) The controller parameters

Compared to outer-loop control, it is observed that the parameters of inner-loop control more sensitive to SSO, especially for Kpdg (see Fig. 3).

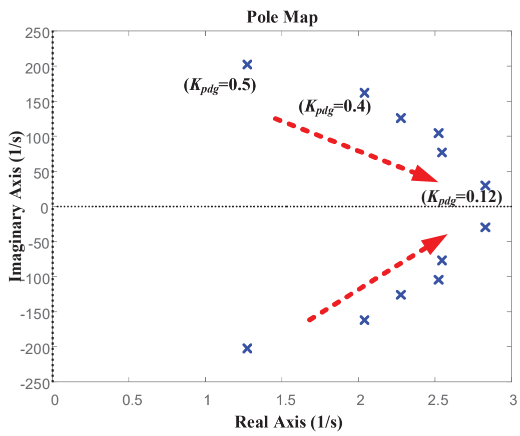
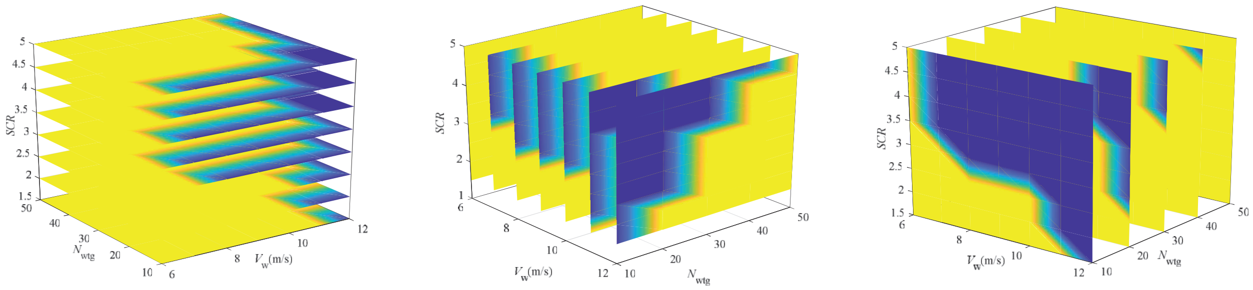


Fig. 9. The eigenvalue identified by Prony method when K_{pdg} decreases from 0.4 to 0.12.



a) b) c)

Fig. 10. The figure of simulation results slices: a) Z-axis (*SCR*) slice plot; b) X-axis (V_w) slice plot; c) Y-axis (N_{wtg}) slice plot.

Taking SSO affected by K_{pdg} as an example, a range of simulations by changing its value are conducted.

The initial simulation conditions are: N_{WTG}=30, SCR=3.25, V_w=12m/s, K_{pdg}=0.5. Next, K_{pdg} varies from 0.5 to 0.12. The Prony results of line current are shown in Fig. 9 and Table V. The results demonstrate that K_{pdg} is sensitive to sub-synchronous damping. Unless the K_{pdg} is big enough, the system will lose stability. In addition, the sub-synchronous frequency decreases accompanied by reducing K_{pdg}.

C. The Possible Safe Operation Range of PMSG-based Wind Farms

From those above analysis, it can be found that multiple factors have apparent impacts on SSO in PMSG-based wind farms, such as SCR, V_w, N_{WTG} and controller parameters. Generally, the controller parameters almost do not change. To specify the safe operation range of PMSG wind farm on the premise of constant controller parameters, we select SCR, V_w, N_{WTG} as variables (SCR∈[1.5, 5], V_w∈[6, 12], N_{WTG}∈[10, 50]). After extensive simulations, we draw three slices plots (see in Fig. 10) displaying the results. The blue part means stable operation state and yellow part refers to unstable SSO state.

It is noteworthy that SCR has a significant influence on SSO. Based on the simulation results, the possible safe operation range of PMSG wind farm is obtained which is shown in Table VI.

TABLE V. PRONY RESULTS STATISTICS

K_{pdg}	Prony results of Ia		
	Frequency of SSO (Hz)	*Damping* (1/s)	*Amplitude* (%)
0.5	32.191	-0.006	4.1
0.4	25.772	-0.013	4.8
0.3	20.053	-0.018	6.3
0.25	16.635	-0.024	8.6
0.2	12.257	-0.033	11.5
0.12	4.741	-0.095	13.6

TABLE VI. SAFE OPERATION RANGE OF PMSG-BASED WIND FARM

SCR	Safe operation range of wind farm	
	V_w (m/s)	N_{WTGs}
SCR⩽2.5	⩾11	⩽10
2.5<SCR⩽3.5	⩾8	⩽20
4<SCR⩽5	⩾7	⩽40

IV. A FEASIBLE SSO MITIGATION METHOD

According to the above analysis, it can be seen that the increase of number of grid-connected WTGs will increase the risk of SSO. Considering the growing development status of wind energy in Xinjiang, it's not practical to limit the number of grid-connected WTGs. Therefore, it is necessary to mitigate SSO when the scale of wind farm increases. This paper introduces a feasible method based on SSSC.

As a member of flexible AC transmission system (FACTS), SSSC is always connected to the system through a series transformer, as shown in Fig. 11. Generally, SSSC can be equivalent to a controllable voltage source. By injecting controllable offset voltage into line, SSSC can regulate the power flow easily.

When SSO occurs, the point of common coupling (PCC) voltage (see in Fig. 2) will contain sub-synchronous components. Therefore, if we can extract those synchronous components and pass it into SSSC as an additional signal added to the original voltage control signal. The PCC voltage will be compensated completely as long as the additional

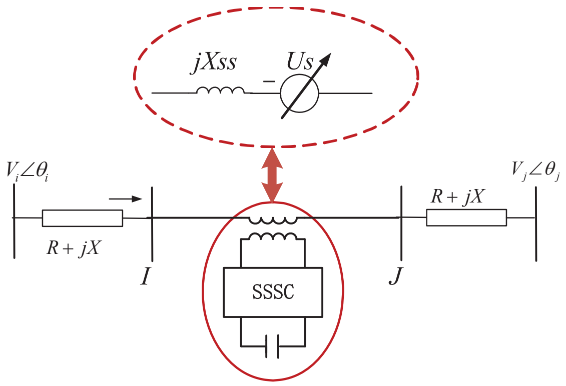


Fig. 11. The schematic of equivalent model of SSSC.

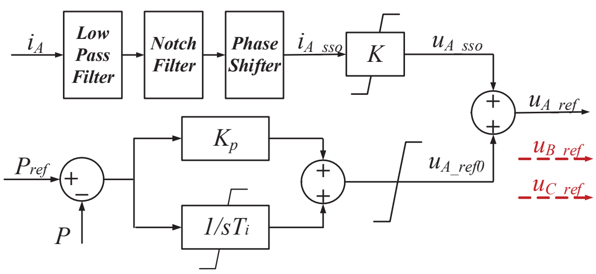


Fig. 12. The additional control block in SSSC.

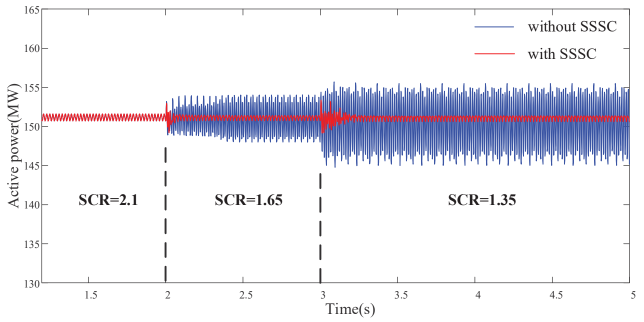


Fig. 13. The verification of additional mitigation strategy.

signal is accurate enough. Follow this route, an additional SSO mitigation control strategy is designed as illustrated in Fig. 12. The i_A is phase-A current signal after eliminating the possible zero sequence component. After passing the low pass filter, notch filter and phase shifter, the sub-synchronous components of i_A, namely i_{A_sso}, is extracted. Then it is multilied by K and passed through limit block. Finally, the additional voltage reference signal is obtained and added it into original signal u_{A_ref0}. Similarly, phase-B (u_{B_ref}) and phase-C (u_{C_ref}) reference voltage are obtained in the same way.

To verify the mitigation effect, an SSSC model containing the additional control block in PSCAD is built with the different calues of SCR at different times. The results are shown in Fig. 13. By comparing the case without SSSC (blue line) with another case with SSSC (red line) under the same changes,it can be concluded that SSSC can suppress the SSO effectively.

V. CONCLUSION

To investigate the new type of SSO incidents in PMSG-based wind farm of Xinjiang grids, this paper establishes the equivalent model of Xinjiang grid based on practical grid data and studies the SSO characteristics of the PMSG-based wind farm by time-domain simulation and Prony method. The following conclusions could be made:

1) The causes of SSO accidents that occur in PMSG-based wind farm of Xinjiang grids are complicated. Multiple factors, especially AC grid strength and control parameters are sensitive to system stability. If inappropriate, the system could lose stability and SSO incidents will occur.

2) Generally, once SSO accidents occur in PMSG-based wind farm, the system damping is extremely weak and even negative. Besides, the sub-synchronous frequency is inversely proportional to damping and oscillation amplitude.

3) Taking the Mahuanggou West wind farm as an example, its possible safe operation range is obtained, which could be a reference for the operation of the wind farm.

4) Combined with an appropriate additional control strategy, SSSC improves system damping significantly. Thus it can be a means of mitigating SSO.

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