Sub-synchronous Oscillation in DFIG and SVG, Controlled by Cooperative Damping Optimization

CH.SRINIVASULU REDDY[1],V.MASTHANAIAH[2],
ASSOCIATE PROFESSOR[1], ASSISTANT PROFESSOR[2],
DEPARTMENT OF EEE
PBR VISVODAYA INSTITUTE OF TECHNOLOGY AND SCIENCE::KAVALI

Abstract—

Large-scale non-synchronized generators and reactive power compensators are two examples of power electronics-based devices that are commonly used in today's power networks. This contributes to the emergence of a novel sub-synchronous oscillatory occurrence brought about by coupling interactions between the devices and the power infrastructure. It plays a vital role in ensuring the reliability of the electrical infrastructure and the equipment that runs on it. This study provides a comprehensive examination of the sub-synchronous fluctuation of the power infrastructure that has been linked to large-scale wind power production. Then, a synchronized dampening optimization control approach is suggested for wind power producers and their reactive power compensators to reduce the sub-synchronous instability. Damping of power electronics is improved by the suggested coordinated control strategy, which follows the sub-synchronous oscillatory current signal to rectify the associated control signal. A self-optimization parameter adjusting technique based on sensitivity analysis is suggested, and the reaction features of the proposed control strategy are examined. The feasibility and viability of the suggested management approach have been verified through modelling.

Key Words—

Sub synchronous vibration generation (SVG), coordinated dampening optimization control (DFIG), and self-optimization parameter adjustment technique (SOPT).

INTRODUCTION

Power electronics-based gadgets have seen widespread use over the past few decades as wind power production has increased. Interactive coupling at the site of shared coupling characterizes power electronics-based devices, especially in the feeble grid. (PCC). Power electronics-based devices' rapid reactions across multiple time periods would improve grid contact with wind generators [1, 2]. Power networks linked to wind energy production are experiencing oscillation issues [4]. At the same time, the oscillatory patterns of the power grid would also be caused by the nonlinearity of the wind turbine control system [5] and the adaptability of the control system of power electronic moving devices [6]. Therefore, it is important to understand the physical process behind power fluctuation in the region, the changing working features of the power grid, and the principles of interplay between the power grid and wind generators. Then, to further strengthen the reliability of the system, the current working and control technology of wind power should be improved. Several studies [7]– [15] have looked into the fluctuation issues of power networks using wind power. The interaction process between the power grid and wind turbines was examined in References [8]–[10], where the stability of the power grid linked to a large-scale wind power was analysed using a small perturbation stability analysis technique. Sub-synchronous control interplay between series compensation and doubly fed induction generator (DFIG)-based wind generators has been investigated in references [11], [12]. In [13], the small disruption power angle stability of the power grid is disclosed after studying the paired interaction mechanism of wind generators and the synchronous machine.

Sub-synchronous oscillations: their characteristics and the physics behind them

A large number of wind generators in the Kumul wind power cluster in Xinjiang, Northwest China, turned off due to power fluctuations in the system on multiple occasions in 2014. Overvoltage or overcurrent in the wind generators caused by the electricity fluctuations caused them to fail. The fluctuation rates were quite broad, ranging from the several hertz to the hundreds of hertz. Voltage and current recorded in a dynamic reactive power correction device during a grid disruption are displayed in Figure 1. With an interval of about, the reactive power of the dynamic reactive power correction mechanism oscillates regularly. 40 ms, meaning that the electricity system is experiencing sub-synchronous fluctuation at 25 Hz [18]. This paper focuses on how powerful interactions between power circuits can give rise to a novel oscillation type known as sub-synchronous

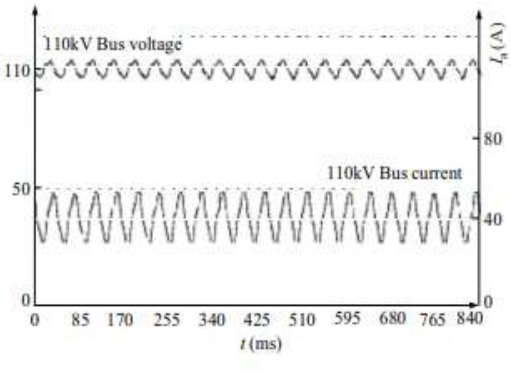


Fig. 1. Measured voltage and current curves of sub-synchronous oscillation.

oscillation. Insight into the underlying process of fluctuation is crucial for enhancing the reliability of the electricity system. Sub-synchronous fluctuation in poor grid integration of large-scale wind power is first and foremost a result of the robust interactions between wind turbines, dynamic reactive power correction device, power grid, and associated management methods. Wind generators and dynamic reactive power correction devices typically do not have a control feature for reducing sub-synchronous oscillations. The wind rotor is set to a specific power factor that is determined by the needs of the wind farm. Voltage management, reactive power compensation, and set power factor control are all capabilities of dynamic reactive power compensation devices. As a result, a wind turbine or dynamic reactive power correction device will make constant adjustments to power in response to a sub-synchronous fluctuation signal. As the bus voltage fluctuates during dynamic regulation, the dynamic reactive power correction mechanisms follow suit to ensure that the required reactive power is maintained without interruption. To account for the presence of sub-synchronous oscillatory frequency components in the power, the wind turbine follows the control order of active power and reactive power to modify the control current in response to the varying bus voltage. Therefore, the voltage shift is more ferocious due to the chaotic management of power electronics-based devices, and the fluctuation is widened.

Sub synchronous fluctuation in Kummel, Xinjiang, is caused by a number of factors, the most important of which is the powerful interplay between wind turbines and the dynamic reactive power correction mechanism. Sub-synchronous oscillation control through coordinated damping optimization This analysis shows that the mechanism of sub-synchronous oscillation is the strong interactions among power electronics, where the initial disturbance signal is amplified by the sub-synchronous response current under a grid disturbance under the uncoordinated control strategies of DFIG and SVG [19]. Sub synchronous oscillation relies heavily on the DFIG reactive power voltage control loop, which is determined by the rotor stimulation voltage magnitude and phase control [26]. The AC bus voltage is held steady by the SVG's AC voltage control loop, a crucial component of the sub-synchronous cycle [29]. The suggested control strategy mainly employs proportional and differential controls, with a straightforward framework, with an eye toward engineering applications. Second, DFIG and SVG can work together to ensure optimal dampening of sub-synchronous oscillations and reduced computational complexity by coordinating their operations based on offline parameter design. This paper proposes a coordinated damping optimization control strategy of sub-synchronous oscillation for DFIG and SVG, the structure of which is depicted in Fig. 2. This strategy is based on the sub-synchronous oscillation mechanism and the response characteristics of the control system to the sub-synchronous oscillation.

Characteristics of the Optimal Control and Self-Optimization Parameter Tuning for Coordinated Damping

The Optimal Control Response Characteristics of the DFIG's Extra Damping

An example of a voltage and flux numerous vector model of DFIG in the d-q spinning reference frame, which is necessary for the suggested extra dampening control of DFIG, is given in [19]. This model is applicable to multiplex kinds of wind turbines.

$$\begin{cases} u_{\mathrm{sd}} = R_{\mathrm{s}} i_{\mathrm{sd}} + \mathrm{d}\psi_{\mathrm{sd}}/\mathrm{d}t - \omega_{\mathrm{s}}\psi_{\mathrm{sq}} \\ u_{\mathrm{sq}} = R_{\mathrm{s}} i_{\mathrm{sq}} + \mathrm{d}\psi_{\mathrm{sq}}/\mathrm{d}t + \omega_{\mathrm{s}}\psi_{\mathrm{sd}} \\ u_{\mathrm{rd}} = R_{\mathrm{r}} i_{\mathrm{rd}} + \mathrm{d}\psi_{\mathrm{rd}}/\mathrm{d}t - \omega_{\mathrm{r}}\psi_{\mathrm{rq}} \\ u_{\mathrm{rq}} = R_{\mathrm{r}} i_{\mathrm{rq}} + \mathrm{d}\psi_{\mathrm{rq}}/\mathrm{d}t + \omega_{\mathrm{r}}\psi_{\mathrm{rd}} \end{cases}$$

$$\begin{cases} \psi_{\mathrm{sd}} = L_{\mathrm{s}} i_{\mathrm{sd}} + L_{\mathrm{m}} i_{\mathrm{rd}} \\ \psi_{\mathrm{sq}} = L_{\mathrm{s}} i_{\mathrm{sq}} + L_{\mathrm{m}} i_{\mathrm{rq}} \\ \psi_{\mathrm{rd}} = L_{\mathrm{r}} i_{\mathrm{rd}} + L_{\mathrm{m}} i_{\mathrm{sd}} \\ \psi_{\mathrm{rq}} = L_{\mathrm{r}} i_{\mathrm{rq}} + L_{\mathrm{m}} i_{\mathrm{sq}} \end{cases}$$

where u is the voltage, Iam the current, ψ is the flux, R is the resistance, L is the inductance, ωr is the synchronous angular velocity, subscript s is the stator component, subscript r is the rotor component, subscript d is the d axis component, subscript q is the q axis component, and subscript m is the mutual interaction component. Referencing small disturbance stability analysis based on the time domain, the following response characteristic equations of a rotor-side converter control are obtained based on (3), (4) and Fig. 2.

$$\begin{cases} \Delta u_{\mathrm{rd}} = R_{\mathrm{r}}\Delta i_{\mathrm{rd}} - \omega_{\mathrm{r}}\beta\Delta i_{\mathrm{rq}} + \left(-K_{\mathrm{d1}}\frac{\mathrm{d}}{\mathrm{d}t} - K_{\mathrm{p1}}\right)\Delta i_{\mathrm{rd}} \\ \left[K_{\mathrm{P}}\left(1+\frac{1}{T_{\mathrm{P}}}\int\right)\Delta P_{\mathrm{E}} - \Delta i_{\mathrm{rd}}\right]K_{\mathrm{D}}\left(1+\frac{1}{T_{\mathrm{D}}}\int\right) \\ \Delta u_{\mathrm{rq}} = R_{\mathrm{r}}\Delta i_{\mathrm{rq}} + \omega_{\mathrm{r}}\beta\Delta i_{\mathrm{rd}} + \left(-K_{\mathrm{d2}}\frac{\mathrm{d}}{\mathrm{d}t} - K_{\mathrm{p2}}\right)\Delta i_{\mathrm{rq}} \\ \left[K_{\mathrm{P}}\left(1+\frac{1}{T_{\mathrm{P}}}\int\right)\Delta Q_{\mathrm{E}} - \Delta i_{\mathrm{rq}}\right]K_{\mathrm{D}}\left(1+\frac{1}{T_{\mathrm{D}}}\int\right) \end{cases}$$

CASE STUDIES AND DISCUSSION

Here, we analyse a real-world power grid to confirm the feasibility and viability of the synchronized dampening optimization control approach of sub-synchronous oscillation suggested in this article for DFIG and SVG. Figure 5 depicts the layout of the research system, including details such as the established capability of wind fields and transmission lines. In this instance, we focus on the west transformer center, four wind farms, and reactive power adjustment devices, all of which are outfitted with 195 MW wind turbines, and we use a combined model of a wind farm based on the multiple equivalent technique. The values for the factors (UN = 690 V, Rs = 0.01 p.u., Rr = 0.01 p.u., Ls = 0.1 p.u., Lr = 0.1 p.u., Lm = 3.5 p.u.) are taken from a real DFIG procedure. Kd = 0.0496, Td = 0.0128, Kp = 4, and Tp = 0.1 are DFIG's tunable control factors. The values of Tm = 0.03 and Ki = 20 and Ti = 0.001 are used to regulate SVG. In the simulation, we see a behavior known as sub-synchronous motion. For the sake of argument, let's say that the SVC in wind farm 2 abruptly loses contact with the power infrastructure, as depicted in Fig. 5. This would result in a voltage variation. Using the normal DFIG control strategy, the traditional DFIG damping control strategy, and the proposed coordinated damping optimization control strategy of sub-synchronous oscillation for DFIG and SVG, three scenarios are created to examine the stability of the power grid under conditions of different active power.

A. Grid Stability with High Wind Farm Activation

In Fig. 6, we see the outcomes of a modeling of the electricity grid's resilience in the face of a grid disruption brought on by the high active power of wind farms. Sub-synchronous oscillations appear in the power grid when grid disturbances occur and the usual management strategy of DFIG is implemented under high active power, as depicted in Fig. 6. The frequency of the voltage oscillations is around 25 hertz, the active power oscillation amplitude is 4.3 MW, and the reactionary power oscillation amplitude is 20.4 Mvar. Sub-synchronous oscillations cannot be fully damped under high active power of wind farms, despite the fact that the conventional dampening control technique of DFIG does decrease oscillation magnitude. Adopting the suggested DFIG and SVG synchronized dampening control approach for sub-synchronous oscillation results in a small oscillation magnitude and rapid weakening of the oscillation. Therefore, the reliability of the electrical infrastructure is enhanced by

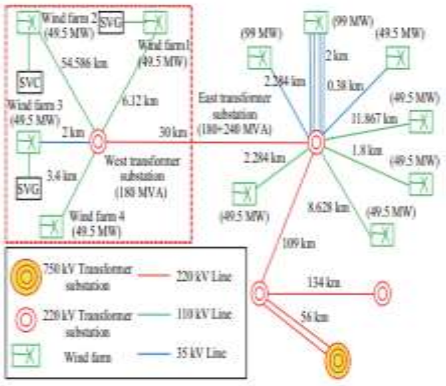


Fig. 5. Single line diagram of the studied power grid.

TIAN et al.: COORDINATED DAMPING OPTIMIZATION CONTROL OF SUB-SYNCHRONOUS OSCILLATION FOR DFIG AND SVG

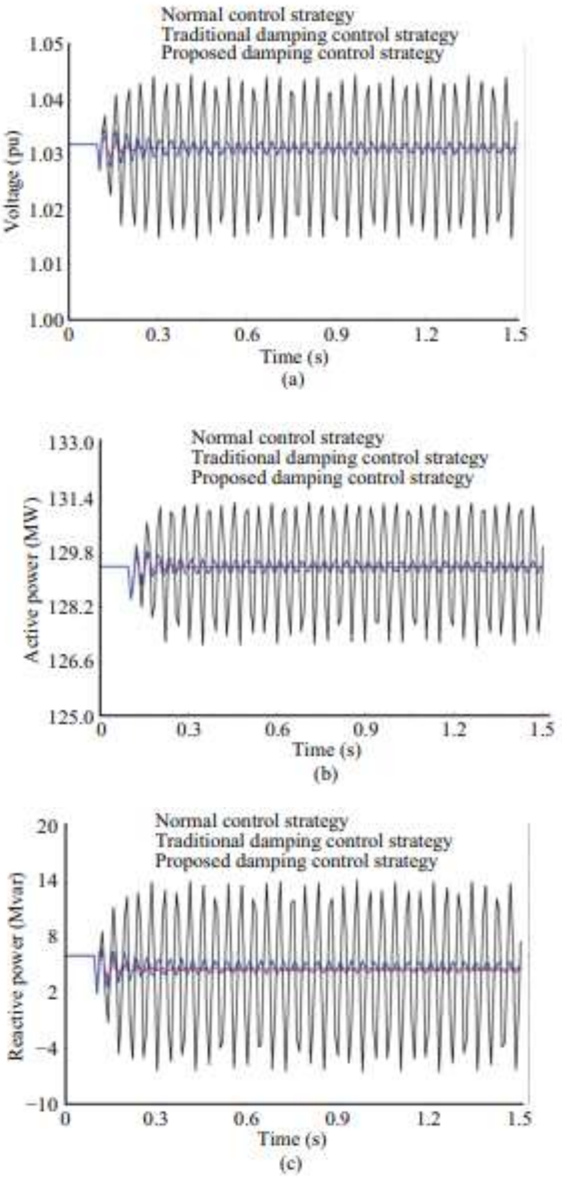
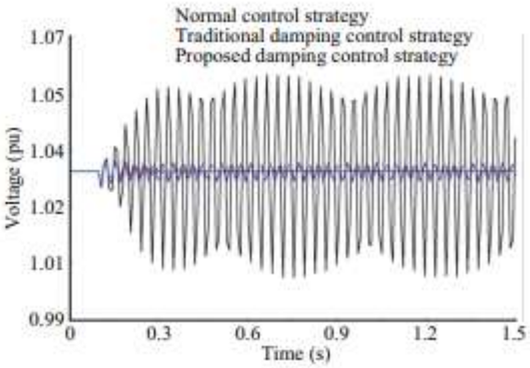


Fig. 6. Stability of the power grid under high active power of wind farms.

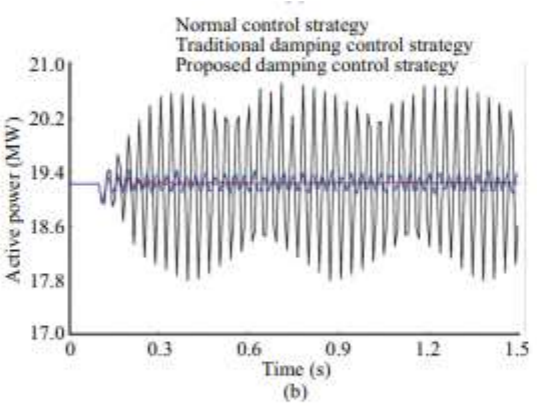
(a) Terminal voltage. (b) Active power of west transformer substation. (c) Reactive power of west transformer substation. the proposed coordinated damping optimization control strategy of DFIG and SVG under high active power during the grid disturbance.

Wind farm impact on grid stability when active power is low

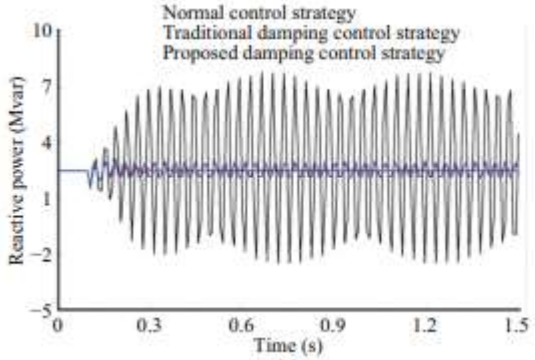
Figure 7 displays the findings of a program investigating the security of the power system in the presence of minimal active power from wind farms. Figure 7 demonstrates that both low and high active power conditions have the same effect on the power grid's dynamic features. Sub-synchronous oscillations also occur when the standard DFIG management technique is used. The voltage amplitude is 0.048 p.u., the active power amplitude is 2.8 MW, the reactive power amplitude is 10.2 Mvar, and the frequency of variation is roughly 25 Hz. While the DFIG's standard dampening control approach can mitigate the effects of the oscillation's sub-synchronous nature, it cannot eliminate it entirely. Adopting the suggested synchronized dampening control for sub-synchronous oscillation results in a rapid weakening of the oscillation magnitude. Therefore, the suggested combined dampening optimization control strategy of DFIG and SVG under low active power during the grid disruption can also ensure the safety of the power grid.



(a)



(b)



(c)

Fig. 7. Stability of power grid under low active power of wind farms. (a) Terminal voltage. (b) Active power of west transformer substation. (c) Reactive power of west transformer substation.

As discussed above, when running simulations with the default management approach of DFIG, sub-synchronous oscillations are observed under grid disruption. Due to the powerful interplay between DFIG and SVG, the efficacy of a conventional DFIG dampening control approach is limited in its ability to suppress the sub-synchronous vibration. The suggested combined dampening optimization control strategy of DFIG and SVG can effectively mitigate the sub-synchronous fluctuation under the varying active power of wind farms, thereby enhancing the stability of the power grid.

CONCLUSION

Sub-synchronous oscillation's underlying physical process is thoroughly investigated. Later, we dive into the specifics of the self-optimization parameter tuning strategy and the synchronized dampening optimization control strategy. The following inferences can be emphasized for clarity: 1) Due to the high density of energy storage resources in DFIG and SVG, energy can be frequently traded between resources during system disturbances. This is the primary cause of the non-synchronous oscillations observed in a DFIG and SVG-connected electricity infrastructure. 2) The suggested synchronized dampening optimization control of DFIG and SVG can be used to reduce the sub-synchronous oscillatory current by adding reaction current. Through these measures, the reliability of the electricity infrastructure serving DFIG and SVG is enhanced. Thirdly, the best DFIG and SVG control parameters can be obtained through synchronized dampening optimization thanks to the self-optimization parameter tweaking approach suggested here. Under non-synchronous frequencies, the synchronized damper control exhibits a superior dampening feature. Both the self-optimization parameter tuning strategy and the synchronized dampening optimization control strategy that were suggested are practical and efficient. Future work will also implement two elements of the present research: DFIG and SVG, with the goal of resolving the sub-synchronous instability issue in a real-world electricity system. Since proportional and differential control technologies are commonly used in engineering, we will first attempt to tackle real sub-synchronous issues using the suggested coordinated damper optimization control technique. Second, a wide variety of cutting-edge control methods for DFIG and SVG will be investigated for reducing sub synchronous oscillations.

REFERENCES

[1] X. M. Yuan, "Integrating large wind farms into weak power grids with long transmission lines," Transactions of China Electrotechnical Society, vol. 22, no. 7, pp. 29–36, Jul. 2007.

[2] X. S. Tian, Y. N. Chi, W. S. Wang, G. Y. Li, H. Y. Tang, and Z. Wang, "Transient characteristics and adaptive fault ride through control strategy of DFIGs considering voltage phase angle jump," Journal of Modern Power Systems and Clean Energy, vol. 5, no. 5, pp. 757–766, Sep. 2017.

[3] Y. K. He and J. B. Hu, "Several hot-spot issues associated with the grid-connected operations of wind-turbine driven doubly fed induction generators," Proceedings of the CSEE, vol. 32, no. 27, pp. 1–15, Sep. 2012.

[4] Y. N. Chi, B. J. Tang, J. B. Hu, X. S. Tian, H. Y. Tang, Y. Li, S. J. Sun, L. Shi, and L. Shuai, "Overview of mechanism and mitigation measures on multi-frequency oscillation caused by large-scale integration of wind power," CSEE Journal of Power and Energy Systems, vol. 5, no. 4, pp. 433–443, Nov. 2019.

[5] N. Karakas is, E. Tsakoumis, N. Jabbour, A. M. Bazzi, and C. Mademlis, "Optimal efficiency control in a wind system with doubly fed induction generator," IEEE Transactions on Power Electronics, vol. 34, no. 1, pp. 356–368, Jan. 2019.

[6] H. K. Tyll and F. Schettle, "Historical overview on dynamic reactive power compensation solutions from the begin of AC power transmission towards present applications," in Proceeding of 2009 IEEE/PES Power Systems Conference and Exposition, 2009, pp. 1–7.

[7] C. Chen, W. J. Du, H. F. Wang, and Tim Littler, "Sub-synchronous Oscillations in Power Systems Caused by Grid-connected Wind FarmsA Survey of Mechanism Studies," CSEE Journal of Power and Energy Systems, vol. 4, no. 4, pp. 495–503, Dec. 2018.

[8] X. R. Xie, H. K. Liu, J. B. He, and W. Liu, "Small-signal impedance/ admittance network modeling for grid-connected renewable energy generation systems," Automation of Electric Power Systems, vol. 41, no. 12, pp. 26–32, Jun. 2017.

[9] H. Geng, X. Z. Xi, and G. Yang, "Small-signal stability of power system integrated with ancillary-controlled large-scale DFIG-based wind farm," IET Renewable Power Generation, vol. 11, no. 8, pp. 1191–1198, Jun. 2017.

[10] S. Abulanwar, W. H. Hu, Z. Chen, and F. Iov, "Adaptive voltage control strategy for variable-speed wind turbine connected to a weak network," IET Renewable Power Generation, vol. 10, no. 2, pp. 238–249, Feb. 2016.

[11] M. Wu, L. Xie, L. Cheng, and R. F. Sun, "A study on the impact of wind farm spatial distribution on power system sub-synchronous oscillations," IEEE Transactions on Power Systems, vol. 31, no. 3, pp. 2154–2162, May 2016.

[12] S. O. Faried, I. Unal, D. Rai, and J. Mahseredjian, "Utilizing DFIG-based wind farms for damping subsynchronous resonance in nearby turbinegenerators," IEEE Transactions on Power Systems, vol. 28, no. 1, pp. 452–459, Feb. 2013.

[13] A. C. Xue, Q. Wang, and T. S. Bi, "Study on the mechanism of small signal dynamic interaction between doubly-fed induction generator and synchronous generator," Proceedings of the CSEE, vol. 36, no. 2, pp. 417–425, Jan. 2016.

[14] L. Wang, X. R. Xie, Q. R. Jiang, H. Liu, Y. Li, and H. K. Liu, "Investigation of SSR in practical DFIG-based wind farms connected to a series-compensated power system," IEEE Transactions on Power Systems, vol. 30, no. 5, pp. 2772–2779, Sep. 2015.

[15] J. Lu, P. Dong, G. Shi, X. Cai, and X. L. Li, "Subsynchronous ¨ oscillation and its mitigation of MMC-based HVDC with large doublyfed induction generator-based wind farm integration," Proceedings of the CSEE, vol. 35, no. 19, pp. 4852–4860, Oct. 2015.

[16] H. K. Liu, X. R. Xie, J. B. He, T. Xu, Z. Yu, C. Wang, and C. Y. Zhang, "Subsynchronous interaction between direct-drive PMSG based wind farms and weak AC networks," IEEE Transactions on Power Systems, vol. 32, no. 6, pp. 4708–4720, Nov. 2017.

[17] Y. H. Xu and Y. P. Cao, "Sub-synchronous oscillation in PMSGs based wind farms caused by amplification effect of GSC controller and PLL to harmonics," IET Renewable Power Generation, vol. 12, no. 7, pp. 844–850, May 2018.

[18] B. Yao and Y. F. Fan, "Analysis and countermeasure research on the cause of oscillation in clusters of wind power," Renewable Energy Resources, vol. 33, no. 8, pp. 1123–1129, Aug. 2015.

[19] Y. N. Chi, X. S. Tian, H. Y. Tang, and X. Li, "Interactions between DFIGs and SVG and oscillation characteristics of power grid connected wind turbines," Power System Technology, vol. 41, no. 2, pp. 486–492, Feb. 2017.

[20] W. Xia and J. S. Kang, "Stability of LCL-filtered grid-connected inverters with capacitor current feedback active damping considering controller time delays," Journal of Modern Power Systems and Clean Energy, vol. 5, no. 4, pp. 584–598, Jul. 2017.