The 6th International Conference on Renewable Power Generation (RPG)

19–20 October 2017

Reactive power control strategy of DFIG-based wind farm to mitigate SSO

Xi Wu[1,2], *Yajing Guan*[1], *Wei Ning*[1]

[1]*School of Electrical Engineering, Southeast University, Nanjing, People's Republic of China*
[2]*Jiangsu Provincial Key Laboratory of Smart Grid Technology and Equipment, Nanjing, People's Republic of China*
E-mail: wuxi@seu.edu.cn

Published in *The Journal of Engineering*; Received on 9th October 2017; Accepted on 1st November 2017

Abstract: Wind farms connected with series compensated transmission network suffer from the risk of sub-synchronous oscillation (SSO). Moreover, the strong active and reactive power control ability of doubly fed induction generator (DFIG) exerts non-negligible influence on SSO. In this study, the impacts of adjustable parameters on SSO are studied based on eigenvalue analysis. The results indicate that increasing inductive reactive power produced by DFIG can provide positive damping to the system; furthermore, the universality of this rule is verified in the whole operating region of DFIG. According to the rule, a reactive power control strategy of DFIG is proposed for SSO suppression. The reactive power is suggested to increase gradually once the SSO is detected and stop until SSO is suppressed or the reactive power limit is reached. The proposed control method is a low-cost method, which only need to adjust the reactive power reference value of DFIG to damp SSO. Finally, the time-domain simulation results illustrate the validity and adaptability of the proposed SSO reactive power control strategy.

1 Introduction

With the increase of construction of large wind power plant in China, the wind power installed capacity keeps growing. The capacitive series compensation of long transmission lines is an effective method to increase the transmission capacity of wind power system. However, one of the hindering factors for the extensive use of series capacitive compensation is the potential risk of sub-synchronous oscillation (SSO) [1, 2]. In recent years, SSO occurred in many countries when wind power is transmitted from doubly fed induction generator (DFIG) based wind farm through series compensated lines. These accidents led to large-scale disconnection of wind turbines from power grid and the damage of crowbar circuit [3–5]. These accidents have attracted the attentions of a large number of scholars.

The influence of operation parameters of wind power transmission systems on the characteristic of SSO has been studied in [6–10], which indicated that wind speed, series compensation, line resistance, and inner loop scale factor of rotor-side convertor (RSC) have great effect on SSO. The main limitation of this research is that only fixed operating condition of DFIG is considered. However, with the development of control technology, the active and reactive power control capability of DFIG is becoming more flexible [11–13], which lead to a larger operation range of DFIG. Therefore, if adjustable parameters like active and reactive power of DFIG are taken into account, it is necessary to study the characteristic of SSO in a larger operation range.

A lot of studies on the suppression strategy of SSO have been conducted. In [10, 14–16], many kinds of supplementary damping controllers were designed and installed in wind turbine controllers, which achieved good inhibition effect. However, the application of this technique is high-cost because hundreds of DFIGs in wind farm should be retrofitted. Furthermore, the influence of the variation of the operation state on SSO cannot be ignored. For example, the output characteristic of DFIG and the control mode of FACTS [17–20] both have influence on the robustness of damping controller [21, 22].

Above all, it is of great practical value to seek a control strategy which has small control cost but strong adaptability to the operation state of the system. The control cost will be obviously reduced if the SSO can be suppressed by adjusting the output power of DFIG. In this paper, the influence of the adjustable parameters on SSO is studied firstly. Then, the impact of reactive power produced by DFIG on SSO is investigated in whole operation region. After that, a control method based on the regulation of reactive power is proposed to suppress SSO and the control strategy is also given. Finally, the effectiveness of the control strategy is verified using time domain simulation.

2 Studied system

A model of DFIG-based wind power system is established according to a North China power grid [23]. The equivalent model is shown in Fig. 1.

The wind farm is composed of 1000 identical DFIGs, each of which is 1.5 MW capacity and connected to the same bus through the 0.69/35 kV transformer T1. A single machine equivalent model [6, 24] is established to simulate the whole DFIG wind farm. The wind farm is connected to the 220 kV line through the 35/220 kV transformer T2, and finally connected to the 500 kV line through the 220/500 kV transformer T3 to realise long-distance transmission of wind power. The series capacitor is installed at the end of the 500 kV line, and the level of series capacitor compensation for the 500 kV line is 8%. In Fig. 1, R_{L1}, X_L1 refer to line resistance and reactance in 220 kV voltage level, R_{L2}, X_{L2} are line resistances and reactance in 500 kV voltage level and X_C represents capacitance of series capacitor.

3 Influence of adjustable parameters of DFIG on SSO

3.1 Adjustable parameters of DFIG

In the operation of wind power transmission system, the adjustable parameters are the reference values of four control variables in RSC and grid-side converter (GSC), respectively, P_{s_ref}, Q_{s_ref}, U_{dc_ref}, Q_{g_ref}. When the reference values above are adjusted, the active and reactive power P_s, Q_s generated by stator, the DC bus voltage U_{dc} and the reactive power Q_g generated by GSC will change as well.

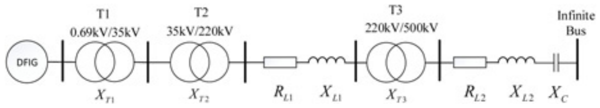

Fig. 1 *Target wind farms and series compensated system*

3.2 *Influence of active power produced by DFIG on SSO*

In the condition that wind speed is 10 m/s (the P_{s_ref} is 0.56 if maximum power point tracking is used) and series compensation level is 8%, the active power produced by DFIG is regulated from 0.5 to 0.1 (the change step length is 0.1). The root loci of SSO mode is shown in Fig. 2.

It can be seen from the figure that the active power generated by DFIG has little influence on the SSO mode. Besides, the real part of SSO mode will increase if DFIG generated less active power, and this means the SSO is more likely to occur. It can be concluded that it is better to keep maximum power point tracking mode and do not adjust active power when SSO occurs.

3.3 *Influence of DC bus voltage on SSO*

In the same condition that wind speed is 10 m/s and series compensation level is 8%, the DC bus voltage U_{dc_ref} is regulated from 1000 to 1300 (the change step length is 100). The root loci of SSO mode is shown in Fig. 3.

It can be concluded that the SSO mode is almost invariant when DC bus voltage changed. Thus, regulating DC bus voltage has no influence on SSO.

3.4 *Influence of reactive power produced by DFIG on SSO*

The reactive power generated by the stator of DFIG [25] is taken as an example when study the influence of reactive power on SSO. In the same operation condition as above, the Q_{s_ref} is regulated from −0.4 to 0.4 pu (the change step length is 0.1 and the negative value represents DFIG generated capacitive reactive power, the positive value represents DFIG generated inductive reactive power). Then, the root loci of SSO mode is shown in Fig. 4.

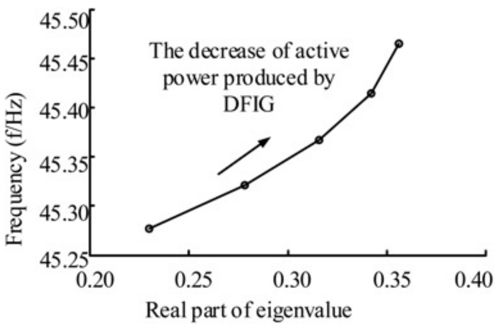

Fig. 2 *Impact of active power produced by DFIG on SSO model*

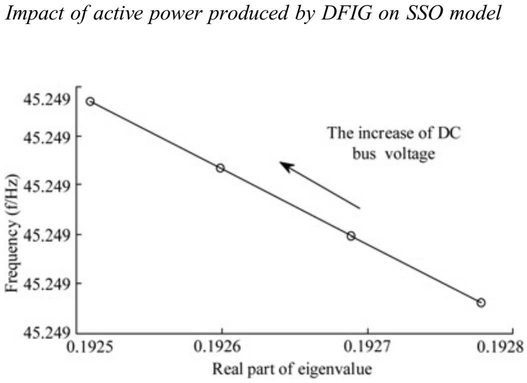

Fig. 3 *Impact of DC bus voltage on SSO model*

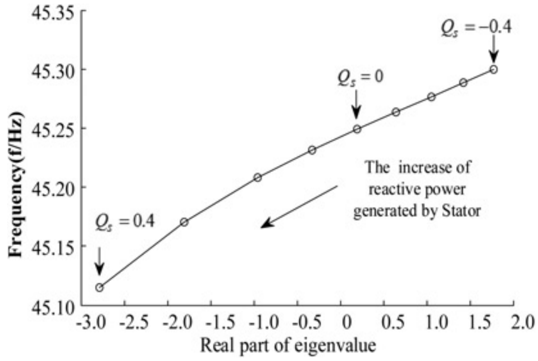

Fig. 4 *Impact of reactive power produced by stator on SSO model*

It can be concluded that the reactive power has great influence on SSO mode. When DFIG produced capacitive reactive power, the real part of SSO mode moved to the positive direction. This means the capacitive reactive power provided negative damping to the system, which is more likely to result in SSO. On the contrary, when DFIG produced inductive reactive power, the real part of SSO mode moved to the negative direction, which means the inductive reactive power provided positive damping and as a result, the phenomenon of SSO is less likely to occur. It is verified that the reactive power generated by GSC has similar impact on SSO and this paper would not state the detail again.

In order to verify the universality of the rule obtained above, the influence of reactive power on SSO is analysed in whole operation region [26, 27] of DFIG in this paper.

The stability region of DFIG is calculated in the condition that the reactive power output of DFIG is −0.1, 0, 0.1, 0.2, 0.3, 0.4 pu (positive value represented inductive reactive power); the result is shown in Fig. 5.

The red curves represent the stable boundaries under cases of different reactive power output of DFIG. The area on the right side of each red curve is stable operation region and the left side is the unstable region. It can be concluded that the more the inductive reactive power produced by DFIG, the larger the stable operation region. This means additional inductive reactive power can always enlarge the stable operation region of DFIG at any operating point in the whole operation region. Therefore, increasing reactive power is beneficial to mitigate SSO when the system is disturbed or in emergency. Further, this paper will study the reactive power control strategy to suppress SSO.

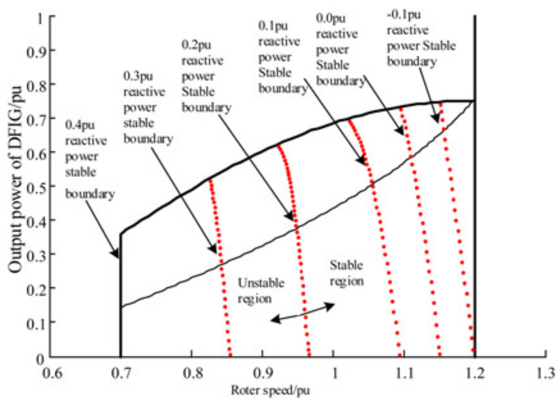

Fig. 5 *Impact of reactive power control in entire operation region*

4 Reactive power control strategy of DFIG to mitigate SSO

4.1 Advantages and disadvantages of reactive power control strategy for SSO mitigation

Adding inductive reactive power of DFIG to suppress SSO has the following advantages:

(i) *Low control cost*: Using supplementary damping controllers to suppress SSO will lead large investment cost, because hundreds of DFIGs in wind farm need to be retrofitted. While, adjusting the reactive power of wind farm only need to change the reactive reference value.
(ii) *Strong robustness*: The supplementary damping controllers which set up for certain operating states is lack of robustness because of the flexibility of running state of DFIG. However, adjusting reactive power has a stable inhibitory effect on SSO in the whole operating regain of DFIG and has better robustness.
(iii) *Less negative effect on system*: Compared with removal of wind turbine from the power grid, adjusting reactive power to alleviate SSO has less negative impact on the system when SSO occurs.
(iv) However, adjusting reactive power to suppress SSO has the following drawbacks:

(i) It is just a control measure in case of emergency, but the risk of SSO cannot be eliminated fundamentally. Actually, adjusting reactive power to suppress SSO only changed the operation mode of system. This method is similar to the power adjustment of generator when the low frequency oscillation occurs in the power grid.
(ii) This method may influence the original operating state of the system and may cause the increase of voltage.
(iii) In general, adjusting reactive power to suppress the SSO caused by the change of operating state is very convenient and low-cost. Then, a specific control strategy of adjusting reactive power to avoid SSO is proposed in Section 4.2. In addition, the effect of this strategy on system operation will be analysed as well.

4.2 Reactive power control strategy

There are many uncertain factors in wind power transmission system could cause the change of operation mode, such as wind speed change, wind turbine switching, broken or short circuit fault and so on. The SSO caused by the change of operating state can be suppressed by adjusting reactive power output of DFIG. However, it is difficult to calculate the reactive power needed for SSO mitigation in all operation modes. What is more, it may have great impact on the voltage if generate reactive power to the limitation once the SSO is detected. Therefore, this paper suggested that the reactive power produced by DFIG should be divided into several parts at first (0.15 pu is taken as each part in this example). When SSO is detected, the reactive power should be increased gradually until SSO is suppressed or the reactive power limit is reached. If SSO is suppressed before exceeding the reactive power limit [28] of DFIG, keep current reactive power and wait for the clearing of the fault. Otherwise, send out warning signal to the control system.

The specific control strategies are as follows:

Step 1: The reactive power of the transmission line is monitored on-line, and test signal method (such as total least squares (TLS)–estimation of signal parameters via rotational invariance techniques (ESPRIT) algorithm [29]) is adopted to extract the amplitude, frequency, and attenuation coefficients of SSO mode. If the attenuation coefficients of SSO mode $\tau \leq 0$ keep monitoring; if $\tau > 0$, which indicates that SSO occurs, turn to Step 2.
Step 2: Before adding a part of reactive power, the control system should determine whether the reactive power exceed the limit after adding a part of it. If not, turn to Step 3; otherwise, it means the SSO cannot be suppressed by adjusting reactive power; therefore, the control system should send out warning and conduct other operations, like cutting machine.
Step 3: Adding a part of reactive power.
Step 4: After adding reactive power, the tendency of SSO is detected. Then check whether the trend of attenuation is obvious ($\tau = -0.7$ is taken as the boundary, because at this point the SSO component is attenuated by 50% per second). If $\tau > -0.7$, go back to Step 2; if $\tau \leq -0.7$, which means the tendency of SSO is decreasing obviously, keep present output of reactive power for 20 s and check whether $\tau \leq -0.7$ again. If so, turn to Step 5, otherwise back to Step 2.
Step 5: Judging whether the reactive power strategy is started the second time in 2 min. If not, reset the reference value of reactive power of DFIG to the original value and return to Step 1. Otherwise, maintain the current reactive power and wait for the removal of the fault.

The flow chart of the control strategy is shown in Fig. 6.

4.3 Case study

Time domain simulation is conducted in MATLAB/SIMULINK. The wind speed is set at 9.5 m/s and the disturbance is put into the system at 11 s. The proposed reactive power control strategy is applied to suppress SSO and the simulation results are shown in Fig. 7. In this case, $\Delta t = 1$ s, $\Delta Q = 0.15$ pu, $Q_s(0) = 0$ pu and the limit of inductive reactive power Q_{s_max} generated by DFIG is about 0.70 pu.

The waveforms of active power, reactive power, and phase current are shown in Fig. 7. The SSO is detected 1 s later after

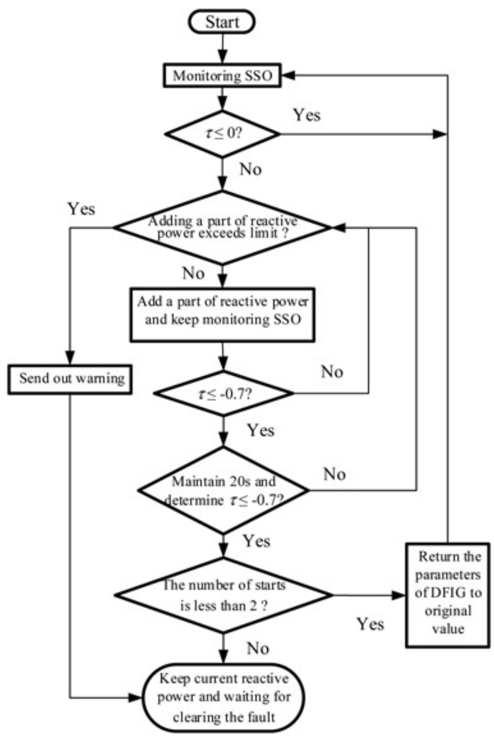

Fig. 6 *Flow chart of reactive power control strategy*

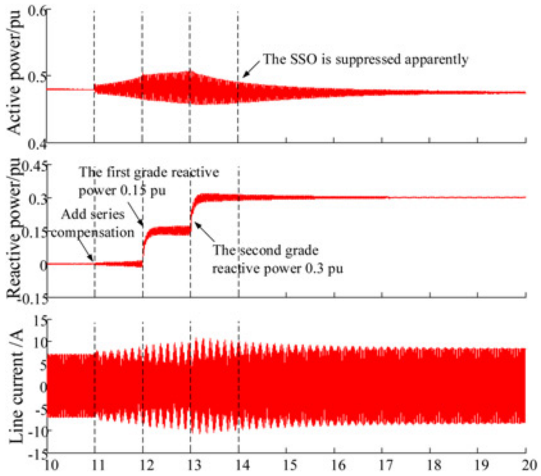

Fig. 7 *Result of reactive power control strategy*

the input of disturbance. Then, the reactive power control strategy is turned on and injected the first part of reactive power, $\Delta Q = 0.15$ pu. One second later, another part of reactive power is added since the tendency of SSO is not obviously reduced ($\tau > -0.7$) after the first part is added. One second later at 14 s, reactive power stopped increasing due to obvious attenuation trend of SSO ($\tau \leq -0.7$). The result indicates that the control strategy can effectively suppress SSO in the system. After maintaining the control strategy for 20 s, the SSO mode has been almost eliminated. Then, the reference value of reactive power can return to original state. If the system could not maintain stable after this operation, restart the reactive power control again and do not exit, because the fault has not been cleared.

Since the voltage has strong correlation with reactive power, the influence of the reactive power control strategy on the voltage has been studied. The change of voltage effective value at the level of 0.69 and 500 kV is shown in Fig. 8.

Fig. 8 indicates that the voltages rise along with the increase of reactive power. The 0.69 kV bus voltage increases to 1.03 pu and the 500 kV bus voltage increases to 1.005 pu after 0.3 pu reactive power are added to the system. The results show that the voltages are still acceptable under the strategy proposed in this paper.

Above all, the reactive power control strategy proposed in this paper can effectively suppress SSO in wind power transmission system. The strategy only needs to control the reference value of the reactive power of DFIG; it is a practical method to suppress SSO with low-cost, strong adaptability and less influence on the system.

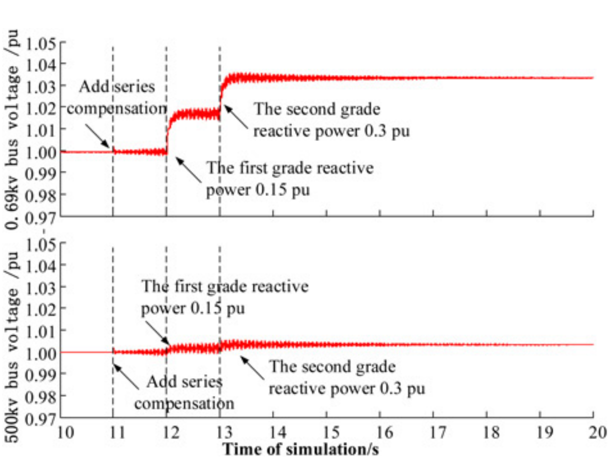

Fig. 8 *Variation of voltage*

5 Conclusion

In this paper, the influence of adjustable parameters on SSO is analysed based on eigenvalue analysis. The results show that increasing inductive reactive power produced by DFIG can provide positive damping for the system, which is very helpful for SSO suppression. Furthermore, the universality of this rule is verified in the whole operation region of DFIG. Based on the rule, a reactive power control strategy of DFIG-based wind farm for SSO mitigation is proposed in this paper. Time domain simulation indicates that the control strategy could effectively suppress SSO. It is a low-cost control strategy, which provides a new way to mitigate SSO in actual operation of wind power system.

6 Acknowledgments

This work was supported in part by the National Natural Science Foundation of China (Grant no. 51407028), the Natural Science Foundation of Jiangsu Province (Grant no. BK20140633), and the project of Jiangsu Provincial Key Laboratory of Smart Grid Technology and Equipment.

7 References

[1] Bi T., Kong Y., Xiao S.: 'Review of sub-synchronous oscillation with large-scale wind power transmission', *J. Electr. Power Sci. Technol.*, 2012, **27**, (1), pp. 1–15

[2] Cheng S., Cao Y., Jiang Q.: 'Sub-synchronous oscillation of power system analysis theory and method [M]' (Science Press, Beijing, 2009)

[3] Adams J., Carter C., Huang S.: 'ERCOT experience with sub-synchronous control interaction and proposed remediation'. Transmission and Distribution Conf. and Exposition (T&D), FL, USA, 2012, pp. 1–5

[4] Narendra K., Fedirchuk D., Midence R., *ET AL.*: 'New microprocessor based relay to monitor and protect power systems against sub-harmonics'. Electrical Power and Energy Conf. (EPEC), MB, Canada, 2011, pp. 438–443

[5] Wang L., Xie X., Jiang Q., *ET AL.*: 'Investigation of SSR in practical DFIG-based wind farms connected to a series-compensated power system', *IEEE Trans. Power Syst.*, 2011, **30**, (5), pp. 2772–2779

[6] Fan L., Kavasseri R., Zhixin L., *ET AL.*: 'Modeling of DFIG-based wind farms for SSR analysis', *IEEE Trans. Power Deliv.*, 2010, **25**, (4), pp. 2073–2082

[7] Ostadi A., Yazdani A., Varma R.K.: 'Modeling and stability analysis of a DFIG-based wind-power generator interfaced with a series-compensated line', *IEEE Trans. Power Deliv.*, 2009, **24**, (3), pp. 1504–1514

[8] Mohammadpour H.A., Ghaderi A., Santi E.: 'Analysis of sub-synchronous resonance in doubly-fed induction generator-based wind farms interfaced with gate-controlled series capacitor', *Gener., Transm. Distrib.*, 2014, **8**, (12), pp. 1998–2011

[9] Li R., Lu Y., Liu H.: 'Mechanism analysis on sub-synchronous oscillation caused by grid-Integration of doubly fed wind power generation system via series compensation', *Power Syst. Technol.*, 2013, **11**, pp. 3073–3079

[10] Gao B., Li R., Yang D.: 'Damping characteristics and countermeasure of DFIG sub-synchronous oscillation', *Electr. Power Autom. Equip.*, 2015, **35**, (12), pp. 11–20

[11] Wang L., Cheng L., Sun Y.: 'A hybrid power modulation damping controller for doubly-fed induction generator', *Power Syst. Technol.*, 2015, **39**, (2), pp. 406–413

[12] Tian J., Su C., Chen Z.: 'Reactive power capability of the wind turbine with doubly fed induction generator'. IEEE IECON 2013-39th Annual Conf. of the IEEE Industrial Electronics Society, Vienna, Austria, 2013, pp. 5312–5317

[13] Li R., Tang F., Liu Y.: 'A new scheme of reactive power compensation and voltage control for DFIG based wind farm', *Proc. CSEE*, 2012, **32**, (19), pp. 16–23

[14] Irwin G.D., Jindal A.K., Isaacs A.L.: 'Sub-synchronous control interactions between type 3 wind turbines and series compensated AC transmission systems'. Power and Energy Society General Meeting, MI, USA, 2011, pp. 1–6

[15] Wang B., Lu J., Gong J.: 'A method to sup-press sub-synchronous oscillation of wind farm composed of doubly fed induction generators

with additional rotor side control', *Power Syst. Technol.*, 2013, **37**, (9), pp. 2580–2584
[16] Li H., Chen Y., Zhao B.: 'Analysis and control strategies for depressing system sub-synchronous oscillation of DFIG-based wind farms', *Proc. CSEE*, 2015, **35**, (7), pp. 1613–1620
[17] Varma R.K., Auddy S., Semsedini Y.: 'Mitigation of sub-synchronous resonance in a series-compensated wind farm using FACTS controllers', *IEEE Trans. Power Deliv.*, 2008, **23**, (3), pp. 1645–1654
[18] Moharana A., Varma R.K., Seethapathy R.: 'SSR mitigation in wind farm connected to series compensated transmission line using STATCOM'. Power Electronics and Machines in Wind Applications (PEMWA), CO, USA, 2012, pp. 1–8
[19] Mohammadpour H.A., Santi E.: 'Sub-synchronous resonance analysis in DFIG-based wind farms: mitigation methods – TCSC, GCSC, and DFIG controllers – Part II'. Energy Conversion Congress and Exposition (ECCE), PA, USA, 2014, pp. 1550–1557
[20] Golshannavaz S., Aminifar F., Nazarpour D.: 'Application of UPFC to enhancing oscillatory response of series-compensated wind farm integrations', *IEEE Trans. Smart Grid*, 2014, **5**, (4), pp. 1961–1968
[21] Wu X., Jiang P.: 'Research on sub-synchronous oscillation mitigation using supplementary excitation damping controller and thyristor controlled series capacitor', *Proc. CSEE*, 2012, **27**, (4), pp. 179–184
[22] Wu X., Jiang P.: 'Sub-synchronous damping controller design based on practical stability region', *Proc. CSEE*, 2013, **33**, (25), pp. 123–129
[23] Wang L., Xie X., Jiang Q.: 'Analysis and mitigation of SSR problems in large-scale wind farms with doubly-fed wind turbines', *Autom. Electr. Power Syst.*, 2014, **38**, (22), pp. 26–31
[24] Li H., Yang C., Zhao B., *ET AL.*: 'Aggregated models and transient performances of a mixed wind farm with different wind turbine generator systems', *Electr. Power Syst. Res.*, 2012, **92**, pp. 1–10
[25] Wang S., Li G., Zhou M.: 'The reactive power adjusting mechanism & control strategy of doubly fed induction generator', *Proc. CSEE*, 2014, **16**, pp. 2714–2720
[26] He Y., Hu J., Xu L.: 'Grid doubly-fed asynchronous wind turbine operation control' (China Electric Power Press, Beijing, 2011)
[27] Dong X., Xie X., Liu H.: 'SSR characteristics of a wind farm connected to series-compensated transmission system under all operation region of DFIG', *Power Syst. Technol.*, 2014, **38**, (9), pp. 2429–2433
[28] Engelhardt S., Erlich I., Feltes C., *ET AL.*: 'Reactive power capability of wind turbines based on doubly fed induction generators', *IEEE Trans. Energy Convers.*, 2011, **26**, (1), pp. 364–372
[29] Wu X., Jiang P., Luo X.: 'SSO mitigation using supplementary excitation damping controller based on TLS–ESPRIT', *Electr. Power Autom. Equip.*, 2009, **10**, pp. 25–29