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SSO of DFIG-based wind farm integrated by a hybrid series compensator

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Abstract: Doubly-fed induction generator (DFIG)-based wind farms integrated by series compensated transmission lines are confronting with the problem of subsynchronous oscillation (SSO). In this study, the configuration and control stratagem of hybrid series compensator composed of a static synchronous series compensator (SSSC) and a fixed capacitor are proposed, and the SSO of DFIG-based wind farm integrated by a hybrid series compensator are studied. The results reveal that the SSO risk of the system is lower by using the hybrid series compensator, and the SSO damping is larger with a higher proportion of SSSC in the hybrid series compensator, as well as with a larger compensation impedance or voltage of SSSC. The research is supposed to be helpful for the planning and operating of the power system with large-scale wind farms integrated.

1 Introduction

Wind energy is one of the most promising forms of renewable energy so far, and the trend of wind energy development is integrating large-scale wind farms that are popularly equipped with doubly-fed induction generators (DFIGs) into the bulk transmission system directly [1–3]. In some countries like China, the resources of wind energy are concentrated in areas that are far away from the load centre. Hence, to improve the transmission capacity of the power system, series compensated transmission lines are extensively used in the power systems [4–6].

For integration projects of a large-scale wind farm, good economical profit can be achieved by using fixed series capacitor compensators; however, the risk of subsynchronous oscillation (SSO) could be brought to the system at the same time [7, 8]. It has been reported that incidents of SSO caused by fixed series capacitors have been observed in some DFIG-based wind farms that are located in China and America, and electric power facilities like crowbar circuit were damaged [6–8].

A static synchronous series compensator (SSSC) can inject a voltage whose phase is leading/lagging the phase of the line current by 90°; thus, the degree of the series compensation can be improved equivalently. In addition, it is believed that SSSC is less risky to cause SSO of a turbine generator in several publications [9–11]. Therefore, it may be a promising option by utilising a fixed series capacitor and SSSC as a hybrid series compensator to increase the transmission capacity of the power system and to get good economical profit.

For the SSO study of the power system equipped with SSSC or hybrid series compensator, existing research works are devoted to the turbine generator unit system, whereas very limited studies have been performed or published on the SSO of DFIG-based wind farms that are integrated by hybrid series compensators [12–15]. Therefore, it should be significant for the integration program of a large-scale wind farm to study the SSO of DFIG-based wind farms integrated by a hybrid series compensator.

The rest of this paper is organised as follows. The configuration and control strategy of the hybrid series compensator are deduced and proposed in Section 2. Section 3 gives the configuration and parameters of the test system in which a DFIG-based wind farm is integrated radially by a hybrid series compensator, and the SSO of this test system is studied and analysed in Section 4. Conclusion remarks are given in Section 5.

2 Hybrid series compensator

2.1 Configuration and principle of the hybrid series compensator

A hybrid series compensator is composed of a fixed capacitor and an SSSC, and its configuration is shown in Fig. 1.

Ignoring the loss of SSSC, the output voltage of SSSC $\dot{U}_{12}$ would be orthogonal to the line current $\dot{I}_{\text{line}}$, and consequently, the equivalent reactance of the hybrid series compensator would be

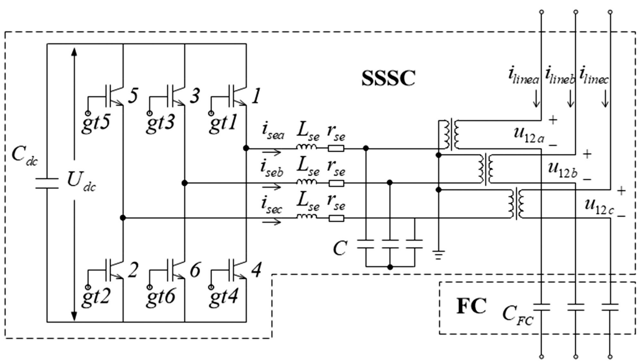

Fig. 1 *Configuration of the hybrid series compensator*

$$X_{eq} = \frac{\dot{U}_{12}}{\dot{I}_{line}} + \frac{1}{j\omega_s C_{FC}} \tag{1}$$

where ω_s is the angular frequency of the power system and C_{FC} is the value of the fixed capacitor.

According to (1), the equivalent reactance of the hybrid series compensator X_{eq} can be regulated by controlling the amplitude and phase of the SSSC output voltage $\dot{U}_{12}$.

2.2 Control strategy of the converter

In this paper, the converter of the hybrid series compensator is controlled in a dq-frame synchronised to the line current $\dot{I}_{line}$ that flows through the hybrid series compensator, and the q-axis component of $\dot{I}_{line}$ is forced to zero, i.e. the d-axis and q-axis components of $\dot{I}_{line}$ are

$$\begin{cases} I_{lined} = I_{line} \\ I_{lineq} = 0 \end{cases} \tag{2}$$

According to (2), the q-axis component of SSSC output voltage U_{12q} is orthogonal to the line current $\dot{I}_{line}$ in this dq-frame, and consequently, the reactance/voltage compensation of the SSSC to the system can be realised by regulating the amplitude of U_{12q}.

Meanwhile, ignoring the loss of the converter, the DC voltage U_{dc} of the DC capacitor is regulated by the active power absorbed by the converter and can be represented by

$$\begin{aligned} C_{dc}U_{dc}\frac{dU_{dc}}{dt} &= \left(U_{12d}I_{lined} + U_{12q}I_{lineq}\right) - \left(I_{sed}^2 + I_{seq}^2\right)r_{se} \\ &= U_{12d}I_{lined} - \left(I_{sed}^2 + I_{seq}^2\right)r_{se} \end{aligned} \tag{3}$$

where r_{se} represents the resistance of the terminal branch of the converter and C_{dc} represents the capacitance of the DC capacitor. Therefore, the DC voltage of the DC capacitor can be regulated by controlling the d-axis component of SSSC output voltage U_{12d}.

According to Fig. 1, the current equation and voltage equation of the terminal branches of the converter can be obtained as

$$\begin{cases} I_{sed} = I_{lined} - \omega_s C U_{12q} + C\dfrac{dU_{12d}}{dt} \\ I_{seq} = I_{lineq} + \omega_s C U_{12d} + C\dfrac{dU_{12q}}{dt} \end{cases} \tag{4}$$

$$\begin{cases} U_{sed} = U_{12d} + \left(r_{se}I_{sed} - \omega_s L_{se} I_{seq}\right) + L_{se}\dfrac{dI_{sed}}{dt} \\ U_{seq} = U_{12q} + \left(r_{se}I_{seq} + \omega_s L_{se} I_{sed}\right) + L_{se}\dfrac{dI_{seq}}{dt} \end{cases} \tag{5}$$

where I_{se} and U_{se} are the output current and voltage of the converter, respectively, C is the capacitance of the shunt capacitor of the converter terminal branch and L_{se} is the inductance of the terminal branch of the converter.

From (4) and (5), it can be concluded that the d-axis and q-axis components are coupled in the current and voltage equations of the terminal branches of the converter. Hence, to control the reactance/voltage compensation and DC voltage by U_{12q} and U_{12d}, respectively, feed-forward control is used and the feed-forward variables for (4) and (5) are

$$\begin{cases} I_{sed\_fed} = -\omega_s C U_{12q} \\ I_{seq\_fed} = \omega_s C U_{12d} \end{cases} \tag{6}$$

$$\begin{cases} U_{sed\_fed} = r_{se}I_{sed} - \omega_s L_{se} I_{seq} \\ U_{seq\_fed} = r_{se}I_{seq} + \omega_s L_{se} I_{sed} \end{cases} \tag{7}$$

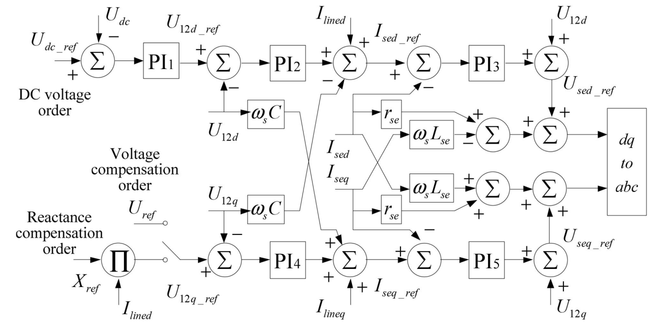

Fig. 2 *Control block diagram of the converter*

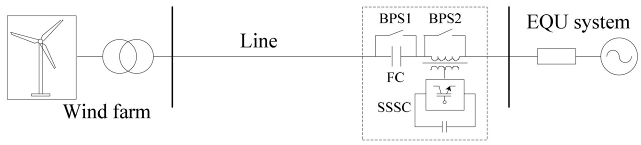

Fig. 3 *Single-line diagram of the wind farm integrated by the hybrid series compensator*

Table 1 Parameters of the SSSC simulation model

Variable	Value
ratio of the series transformer, kV/kV	110/35
capacitance of the DC capacitor C_{dc}, μF	6000
rated voltage of DC capacitor U_{dc}, kV	70
shunt capacitor of the converter terminal branch C, μF	30
inductance of the converter terminal branch L_{se}, H	0.004
resistance of the converter terminal branch r_{se}, Ω	0.2

Table 2 Parameters of the converter control system

Variable	Value	Variable	Value
k_{P1}	0.9524	k_{I1}	1.5238
k_{P2}	0.0635	k_{I2}	30.158
k_{P3}	6.6667	k_{I3}	587.30
k_{P4}	0.0952	k_{I4}	39.682
k_{P5}	6.0317	k_{I5}	587.30

According to (1)–(7), the control strategy of the converter can be deduced, as shown in Fig. 2, where either reactance compensation mode or voltage compensation mode can be selected for the control loop of U_{12q}.

3 Test system

The configuration of the test system is shown in Fig. 3. A series compensated transmission line is used to connect a DFIG-based wind farm to the far away equivalent power system radially, and a hybrid series compensator is utilised in this system.

The parameters of the SSSC are given in Table 1.

The parameters of the converter are given in Table 2, where the subscripts P and I represent the variables for proportional and integral, respectively, and subscripts 1–5 represent the variables for the corresponding PIs in Fig. 2.

4 System studies

The full-scale detailed electromagnetic transient model of the test system is constructed in PSCAD/EMTDC, and the impacts of the hybrid series compensator working either in reactance compensation mode or in voltage compensation mode are studied by simulation.

In the following studies, BPS2 (bypass switch 2) is opened to put the SSSC into service in the initial state, whereas BPS1 is closed to bypass the fixed series capacitor in the initial state, and it is opened at 0.5 s to put the fixed series capacitor into service.

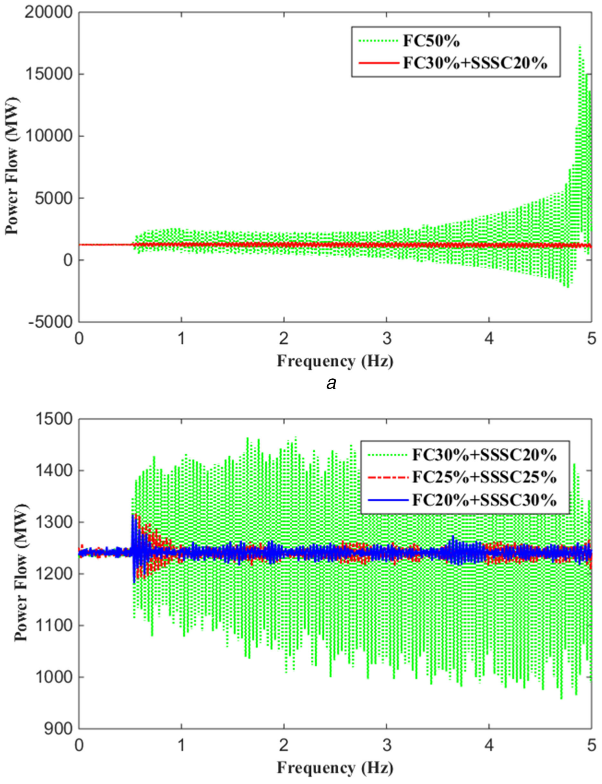

Fig. 4 *Power flow of the wind farm with variable proportion of SSSC in the hybrid series compensator*

4.1 Reactance compensation mode

SSSC in the hybrid series compensator is working in reactance compensation mode.

Fig. 4. shows the simulation results of the active powers of the wind farm when the compensation degree of the hybrid series compensator is 50% and the compensation degrees of the SSSC are 0, 20%, 25% and 30%, respectively.

Figs. 4*a* and *b* show that the system is unstable with just 50% fixed series capacitor compensation, whereas the system becomes stable with the increase of the proportion of SSSC in the hybrid series compensator. Meanwhile, Fig. 4*b* reveals that the system converges quickly after the fixed series capacitor was put into service when the compensation degree of SSSC is 25% or 30%; hence, it can be concluded that there is no need to continue to increase the proportion of SSSC in the hybrid series compensator after the proportion reaches a certain value.

Fig. 5 shows the simulation results of the active powers of the wind farm when the compensation degree of the fixed series compensator is 30% and the compensation degrees of the SSSC are 20%, 30% and 40%, respectively. Fig. 5 suggests that the amplitude of the oscillation decreases with the increase of SSSC compensation reactance, and the system becomes stable finally.

4.2 Voltage compensation mode

SSSC in the hybrid series compensator is working in voltage compensation mode.

Fig. 6 shows the simulation results of the active powers of the wind farm when the compensation degree of the fixed series compensator is 30% and the compensation voltages of the SSSC are 0, 5, 10 and 20 kV, respectively.

Fig. 6 reveals that the system is unstable with just 30% fixed series capacitor compensation, whereas the amplitude of the oscillation decreases with the increase of the SSSC compensation voltage, and the system becomes stable when the compensation voltage of the SSSC is 20 kV.

Either the SSSC works in reactance compensation mode or in voltage compensation mode, simulation results presented above suggested that the SSO risk of the system is lower by using the

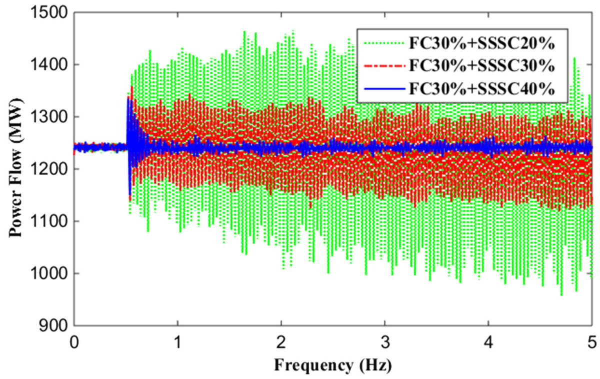

Fig. 5 *Power flow of the wind farm with variable compensation reactance of SSSC*

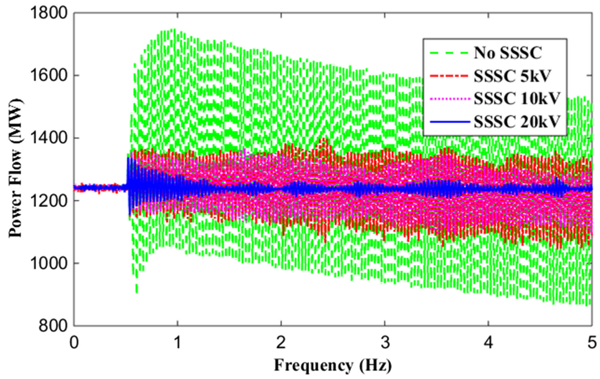

Fig. 6 *Power flow of the wind farm with variable compensation voltage of SSSC*

hybrid series compensator instead of using fixed series capacitor compensator; in addition, the damping of SSO is much stronger with the increase of the compensation reactance, as well as with the increase of the compensation voltage of SSSC.

5 Conclusions

The configuration and control stratagem of the hybrid series compensator are proposed in this paper, and the SSO characteristics of a DFIG-based wind farm integrated radially by a hybrid series compensator are studied by time-domain simulation. The results demonstrate that the following:

(i) The SSO risk of the system is lower by using the hybrid series compensator instead of using the fixed series capacitor compensator.
(ii) The damping of SSO improves with the increase of the compensation reactance or with the increase of the compensation voltage of SSSC.

In the hybrid series compensator, the capacity of the SSSC is always restricted owing to the high cost. Therefore, to improve the stability of the system and to promote the utilisation of the hybrid series compensator, further works will be devoted to the method of using supplementary control of the hybrid series compensator to mitigate the SSO problem of the system.

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7 References

[1] Shu, Y.B., Zhang, Z.G., Guo, J.B., *et al.*: 'Study on key factors and solation of renewable energy accommodation', *Proc. CSEE*, 2017, **37**, (1), pp. 1–8

[2] Zhu, X.Y., Sun, H.S., Wen, J.Y.: 'Subsynchronous interaction and its mitigation in DFIG-based wind farm and turbine-generator bundled systems', *Adv. Mater. Res.*, 2013, **860–863**, pp. 319–323

[3] Chen, G.P., Li, M.J., Xu, T.*, et al.*: 'Study on technical bottleneck of new energy development', *Proc. CSEE*, 2017, **37**, (1), pp. 20–27

[4] Zhu, X.Y., Sun, H.S., Wen, J.Y.*, et al.*: 'Improved complex torque coefficient method using CPCM for multi-machine system SSR analysis', *IEEE Trans. Power Syst.*, 2014, **26**, (5), pp. 2060–2068

[5] Zhu, X.Y., Sun, H.S., Wen, J.Y.*, et al.*: 'A practical method to construct network state equations in multi-machine system SSR study', *Electr. Power Syst. Res.*, 2014, **107**, pp. 51–58

[6] Leon, A.E., Solsona, J.A.: 'Sub-synchronous interaction damping control for DFIG wind turbines', *IEEE Trans. Power Syst.*, 2015, **30**, (1), pp. 419–428

[7] Wang, L., Xie, X.R., Jiang, Q.R.*, et al.*: Investigation of SSR in practical DFIG-based wind farms connected to a series-compensated power system', *IEEE Trans. Power Syst.*, 2015, **30**, (5), pp. 2772–2779

[8] Liu, H.K., Xie, X.R., Zhang, C.Y.*, et al.*: 'Quantitative SSR analysis of series-compensated DFIG-based wind farms using aggregated RLC circuit model', *IEEE Trans. Power Syst.*, 2017, **32**, (1), pp. 474–483

[9] Carpanen, R.P., Rigby, B.S.: 'An improved SSSC-based power flow controller design method and its impact on torsional interaction', *Int. J. Electr. Power Energy Syst.*, 2012, **43**, pp. 194–209

[10] Gyugyi, L., Schauder, C.D., Sen, K.K.: 'Static synchronous series compensator: a solid-state approach to the series compensation of transmission lines', *IEEE Trans. Power Deliv.*, 1997, **12**, (1), pp. 406–417

[11] Pillai, G.N., Ghosh, A., Joshi, A.: 'Torsional oscillation studies in an SSSC compensated power system', *Electr. Power Syst. Res.*, 2000, **55**, (1), pp. 57–64

[12] Pillai, G.N., Ghosh, A., Joshi, A.: 'Torsional interaction studies on a power system compensated by SSSC and fixed capacitor', *IEEE Trans. Power Deliv.*, 2003, **18**, (3), pp. 988–993

[13] Jowder, F.A.R.A., Ooi, B.T.: 'Series compensation of radial power system by a combination of SSSC and dielectric capacitors', *IEEE Trans. Power Deliv.*, 2005, **20**, (1), pp. 458–465

[14] Bongiorno, M., Svensson, J., Angquist, L.: 'On control of static synchronous series compensator for SSR mitigation', *IEEE Trans. Power Electron.*, 2008, **23**, (2), pp. 735–743

[15] Thirumalaivasan, R., Janaki, M.R., Xu, Y.J.: 'Kalman filter based detection and mitigation of subsynchronous resonance with SSSC', *IEEE Trans. Power Syst.*, 2017, **32**, (2), pp. 1400–1409