Subsynchronous Control Interaction: Real-World Events and Practical Impedance Reshaping Controls

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Abstract

The power electronic converters have enabled harnessing of electrical energy from renewable resources, such as wind and solar. However, the power electronic converter controls can interact with other grid components and lead to unstable oscillation in a wide frequency range, for instance, the subsynchronous and high-frequency oscillations. In the past decade, several subsynchronous control interaction (SSCI) events have been reported, for instance, in the Xcel Energy, ERCOT, Guyuan, and Hami wind power systems. This chapter first provides a brief overview of the occurrence mechanisms and features of the real-world SSCI events. Then, it discusses the practical impedance reshaping mitigation control schemes. The practical installation experience of the generator-side and grid-side impedance reshaping controls is shared, which increases the confidence to practically implement these schemes in actual projects in the power industry. Finally, recommended guidelines and research prospects in the analysis and mitigation are provided.

1   Introduction

The technological advancements of power electronic converters and a trend shift from traditional fossil fuel-based power generation have significantly boosted the proportion of renewable resources and the application of power electronics in the modern electric power system. The modern power system with high-penetrations of renewables and power electronics can be called as a "dual high-penetrated power system". The power electronic converters are the key enablers to harvest clean energy from renewable energy sources, such as wind and solar. The wind turbine generators (WTGs) and photovoltaic generators (PVGs) utilize power electronic converters to achieve grid connection and converter/inverter control to maintain and regulate various network parameters, such as voltage and frequency. The converter-based WTGs and PVGs can be jointly named as converter interfaced generators (CIGs). In addition, the power electronic converters have become the backbone of the modern power transmission systems, for instance, flexible AC transmission system (FACTS) and high voltage dc transmission system (HVDC). The "converter control" of the aforementioned power electronic devices can interact with other components of the system at a wide frequency ranging from a few hertz to several kilohertz.

The interactions involving the power electronic converter controls are named as "control interactions". In the past decade, a number of control interaction instability events have been reported around the world. The practical control interaction events indicate that most of the control interactions that involve the converter interfaced generation such as wind and solar are in the subsynchronous frequency range. Thus, the control interactions at the subsynchronous frequency can be called as the subsynchronous control interactions (SSCIs), and the oscillation triggered by the SSCI can be called as the subsynchronous oscillation (SSO). The SSCI could be understood as the interaction phenomenon while the SSO as the cause of the phenomenon.

Based on the system components participating in the interaction, the SSCI can be divided into two types:

1) The SSCI due to the interaction between the converter controls of doubly-fed induction generators (DFIGs) with the series-compensated network [1]. This type of SSCI can occur due to a sudden increase in the series compensation level, sudden decrease in wind speed or the number of in-service DFIGs, or series capacitor switching under certain operating conditions.

2) The SSCI due to the interaction between the converter controls of the permanent magnet synchronous generator (PMSGs)/PVGs and weak AC grid. This type of SSCI can occur due to a sudden increase in the number of in-service PMSGs/PVGs or a sudden decrease in the grid strength.

The control interactions can be intuitively understood in the frequency-domain impedance representation of the whole system. The control interaction occurs when the equivalent resistance of the whole system is negative at certain resonant frequencies. Based on this concept, various frequency-domain impedance analysis and impedance reshaping control techniques have been proposed in the prior literature. In the forthcoming sections, impedance-based analysis and control methods will be discussed particularly.

It is worth mentioning that SSCI is considered as a system-level stability problem. The features of the SSCI are highly influenced by various system-level factors, including the input wind speed or solar irradiance, number of in-service

CIG units, grid configuration or compensation level, grid strength, and weak AC grid. Thus, the local instabilities of the converter controls resulting from incorrect parameters are not considered as the SSCI.

This chapter discusses SSCI events in real-world CIGs in Section 2. Section 3 presents practical SSCI mitigation methods along with the techno-economic comparisons. Recommended guidelines for the SSCI analysis and control are presented in Section 4. Finally, Section 5 ends the paper with concluding remarks.

2. Real-world SSCI events

2.1 Reported events

In the past decade, several SSCI incidents have occurred in wind power systems around the world [2]. Fig. 1 shows timeline of the SSCI events that have been reported. Besides the reported events, there are other events that have not been widely studied or details have not been shared with the scientific community.
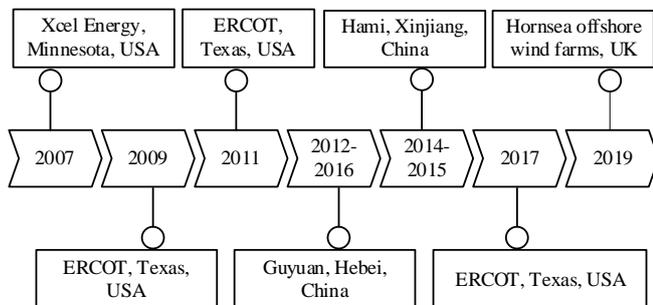

Fig. 1 Timeline of SSCI events in the past decade.

The first SSCI event was reported in 2007 in the Xcel Energy wind power system in Minnesota, USA [3], [4]. The incident occurred when the net series compensation level was increased due to a transmission line fault that left the DFIG-based wind farms in radial connection with the transmission network. The frequency of the SSO due to the SSCI event was around 9 to 13 Hz. A similar SSCI event was observed in the ERCOT wind power system in 2009 in Texas USA. At the time there was no special protection system against the SSO. As a result of the SSCI event, the SSO component in the voltage and current quickly rose and caused severe damages to the series capacitors and crowbar circuits [5]–[8]. This SSCI event was also triggered due to a transmission line fault, leaving the DFIG-based wind farms in radial connection with the series compensated network. The SSCI event in the ERCOT triggered 20 to 30Hz SSO. In 2011, the interaction between PMSGs and the weak AC grid, defined by the low short circuit ratio, caused a very low-frequency oscillation, around 4 Hz. The SSCI event occurred in the ERCOT system in Texas, USA [9], [10]. From 2012 to 2016, many subsynchronous interaction events have been reported in the Guyuan wind power system, causing 6-9Hz SSO [1], [11]. The SSCI occurred when power generated by the DFIG based wind power plant was low due to low wind speed. The induction generation effect and control interaction co-exist while the DFIG's converter controls played a key role in the interaction. In 2014-2015, the event in the Hami wind power

system was caused by the interaction in PMSG-based wind farms connected to the weak AC grid. The SSCI caused strong SSO. Somehow, the triggered frequency of the triggered SSO matched with the torsional frequency of the nearby thermal power generators and excited severe torsional vibration. The structure of the ERCOT wind power system was different due to the addition of various transmission lines and wind farms. In 2017, the SSCI with various oscillation frequencies has been reported. These events were mainly caused by the outage of transmission lines which left the DFIG-based wind farms in radial connection. The SSCI events that occurred in 2017 have been replicated in [12]. In 2019, Great Britain's National Grid experienced a significant power outage [13]. The post-event investigations showed that the converter controls of the Hornsea's offshore PMSGs participated in the event. The dynamics of PVG resemble the PMSG since both use the full converter configuration to achieve grid connection. Although the capacity of the PVG and PMSG converters may be different, the DC to AC control structures is similar. Thus, similar to PMSG connected to a weak AC grid, the PVG could also experience SSCI and trigger unstable sub-/super-synchronous oscillation [14]. Ref. [15] presented field experiences of PVGs resulting in unstable sub-/super-synchronous oscillation.

2.2 Mechanisms and characteristics

Based on the reported SSCI events and the relevant literature, a summary of the mechanisms and characteristics of the SSCI/SSO is presented below.

- SSCI in DFIGs connected to a series compensated transmission line can be caused initiated by a transmission line fault that leaves the DFIG wind farms in radial connection with the rest of the grid. The line fault increases the equivalent series compensation of the grid. Since some of the power generated by the DFIG is sent to the grid directly through the stator, the frequency coupling effect in the DFIG's converter control is not so strong.
- SSCI in DFIG can also be initiated without a transmission line fault and at a very low level of series compensation. The subsynchronous oscillation modes can be excited by switching of series capacitors of the series compensated transmission lines or sudden decrease of the total output power of the wind farms due to dropping of wind speed or number of in-service WTGs.
- SSCI in PMSG or PVG based wind/solar farms can interact with the weak AC grid at the sub-/super-synchronous frequency range. The PMSG/PVGs use full-converters for grid interfacing, thus the frequency coupling effect is very strong.
- A real-world event can be complex, where different phenomena can co-exist. For example, the subsynchronous oscillation triggered by SSCI can match with the nearby turbo generators and excite torsional oscillation (TO). The induction generator effect (IGE) and SSCI can also co-exist. A detailed analysis is required to judge the co-existence of the different phenomena. The events in the Guyuan (IGE + SSCI) and

Hami (SSCI + TO) wind power systems in China, and Hornsea (SSCI + Unknown cause) wind farms in China and UK are examples of such co-existence.

- The magnitude and frequency of the triggered oscillation depend on the system-wide operating conditions, including input renewable resource, number of in-service CIG units, control structure and parameters, level of series compensation, and grid strength. The oscillation frequency for different events in the same or different system can be different. In addition, the oscillation frequency during an SSCI can vary in a wide range due to variations in the parameters, such as the available input renewable resource, the number of in-service CIG units, and network topology.
- Control structure, control parameters, nonlinearities, and PLL's bandwidth have great impacts on the magnitude and frequency of the oscillation.

2.3 Consequences

The initiation and build-up process of the oscillation caused by the SSCI can be very fast. For example, during the 2009 SSCI event in the ERCOT system, the amplitude of the system voltages increased to 150% within 150ms. The sudden increase in current and voltages damaged the series capacitors and the DFIG's crowbar circuits [8]. When the SSCI occurs, the subsynchronous current grows rapidly. Consequently, hundreds of CIGs can be tripped when the current distortions exceeded the preset threshold. This will result in a sudden decrease in wind power being sent to the grid. The frequent decline in wind power seriously threatens the safe and stable operation of the Guyuan wind power system. Besides the equipment damage and renewable energy curtailment, the vibrations and loud noise in the substation transformers speed up the aging of transformer insulation or can even damage the transformers, which makes the equipment less reliable.

4 Impedance reshaping controls

After the SSCI events around the world, a number of techniques have been reported in the literature to mitigate the unstable oscillation triggered due to the SSCI phenomenon. Several SSCI mitigation techniques have been reported in the prior literature [16]–[26]. However, only a few of the mitigation schemes found their way to practical implementation in actual power systems facing the SSCI problem. This paper shares the practical implementation experience of two impedance reshaping-based SSCI mitigation schemes. They have been implemented in the Guyuan wind power system in Northern China.

4.1 Generator-side impedance reshaping control

Similar to the low-frequency oscillation damping in the conventional turbo-generators, the sub-/super-synchronous oscillation triggered by the SSCI can also be suppressed by adding a damping control in the excitation system of each unit with the power system stabilizer (PSS). By doing so, the damping in the oscillation frequency band of each unit respectively can be increased and the dynamic stability of the entire power grid can be improved.

For the DIFG, the rotor side converter (RSC) control has a significant impact on defining the overall rotor's equivalent resistance, the rotor side subsynchronous damping controller (RSDC) should be added in the RSC control [27]. The introduction of RSDC can be understood as a "virtual resistor" which adds positive resistance at the sub-/super-synchronous frequency, thus improving the damping at that frequency range. Fig. 2 shows the RSC control structure with an additional loop for mitigating SSCI. The additional loop consists of an RSDC, which consists of a washout and a proportional derivative controller block.
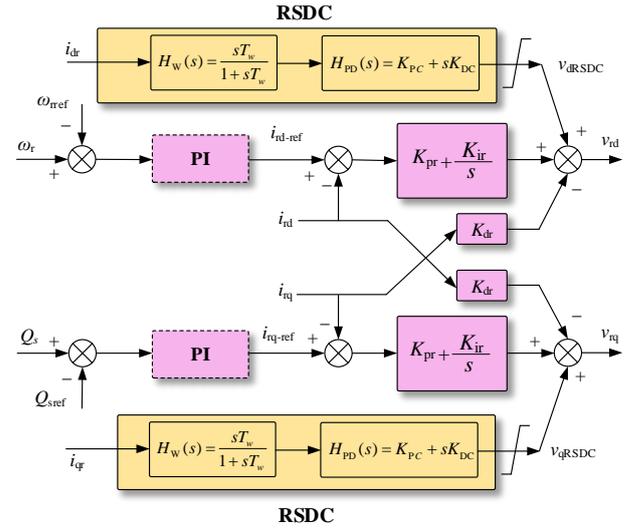

Fig. 2 Rotor-side converter control of a DFIG with RSDC.

The RSDC does not require any dedicated communication channel. It utilizes locally available dq axes currents instead of reference dq currents produced after the outer loop controls. When the unstable oscillation is excited due to SSCI, the RSDC quickly captures the subsynchronous component from the d- and q-axis currents (i_{dr} and i_{qr}) and generates corresponding subsynchronous voltages as output (v_{dRSDC} and v_{qRSDC}), as shown in Fig. 2. The voltage signals act as correction signals added in the output reference voltages. Eventually, the RSDC exhibits itself as a virtual positive resistor added in the rotor side converter control at subsynchronous frequency. The effectiveness and performance of the RSDC for mitigating SSCI have been studied in [28].

The RSDC is designed according to the SSCI events in the Guyuan wind power system. Before installing the modified DFIG's converter control, the SSCI mitigation and dynamic performance including the fault ride-through capability are verified through extensive controller-hardware in the loop (CHIL) tests. The DFIG's converter controls before and after adding the RSDC in the four DFIG units of the LianHuaTan (LHT) wind farm of the Guyuan wind power system are shown in Fig. 3. After field installation, the current, voltage, and power waveforms are continuously monitored. The recorded stator currents along with the corresponding frequency spectrum with and without the RSDC are shown in Fig. 4. The field measurements showed that the oscillation component was significantly suppressed from 264 A to 42.73

A. The suppression of oscillation magnitude after adding the RSDC is shown in Fig. 5 and Fig. 6. The oscillation suppression rate is around 83.83%, which is acceptable for practical implementation of the RSDC in an actual DFIG.
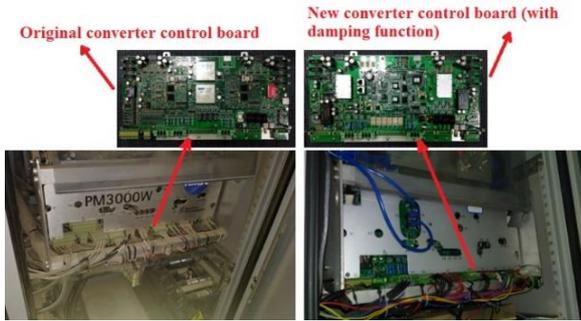

Fig. 3 DFIG converter control boards, Left: original control board, Right: replaced control board with RSDC
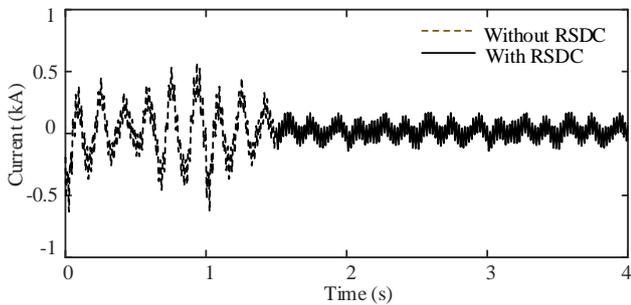

Fig. 4 Field records of an SSCI event before and after switching on the RSDC
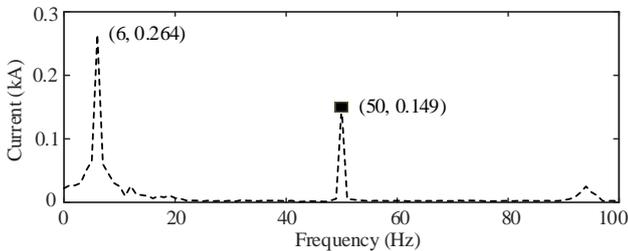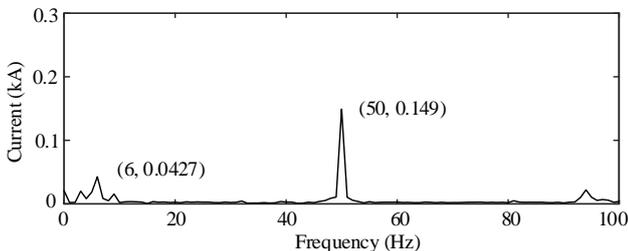

Fig 5 FFT of the recorded current without RSDC

Fig. 6 FFT of the recorded current with RSDC

4.3 Network/Grid-side impedance reshaping control

The impedance response of the whole wind farm or plant can be reshaped by adding a specially designed shunt-connected converter-based damping controller at the network/grid-side [29]. The grid-side subsynchronous damping controller (GSDC) comprises of an SSDC supplemented to a subsynchronous current generator (SCG), as shown in Fig. 7 (a)-(b) [30]. The basic idea is to modify the impedance

characteristics of the system by injecting the currents at the subsynchronous frequency into the system to provide active damping. It consists of two main parts: the SSDC and the SCG. The SSDC utilizes bus voltages and line currents as feedback signals. The subsynchronous currents are extracted and controlled by a combination of properly tuned band-pass and band-stop filters followed by gain and phase shifters. The job of SCG is to generate three phase phase-shifted currents according to the oscillation frequency. The frequency of the oscillation usually known so that the extraction filters and phase shifters can be tuned accordingly. The SCG is an H-bridge converter with an internal controller.
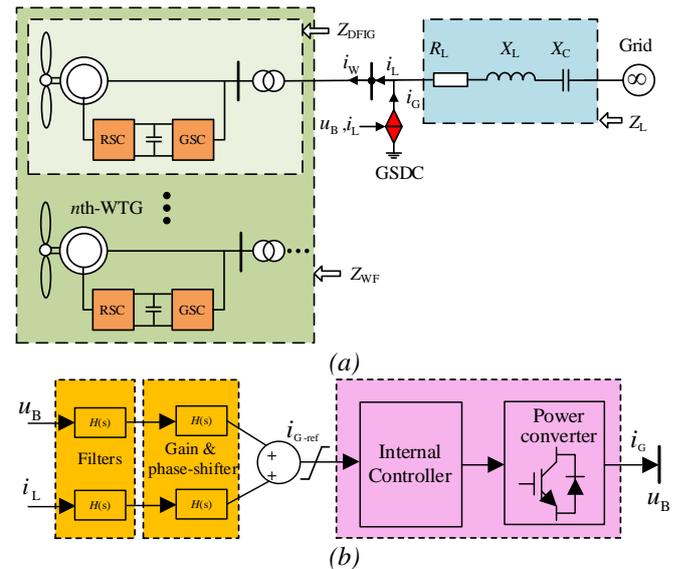

Fig. 7 (a) A typical series compensated DFIG system with GSDC installed at the grid/network (b) Configuration of GSDC [30]

An actual 10MVA GSDC hardware has been developed for the Guyuan system and its damping capability has been validated through CHIL simulations on the Guyuan system's simulation model. The GSDC is connected at the Chabei substation.

In the practical system, the 220-kV Guyuan substation does not have enough space to accommodate a new device to mitigate the SSO. Therefore, GSDC is installed at the 220-kV Chabei substation. The capacity of the GSDC is 10MVA with an operating voltage of 35kV. The GSDC's shunt converter is connected to the grid through a coupling transformer. With this configuration, the GSDC uses the Chabei substation's 220kV bus voltage and line currents as the input control signals. The control signals are locally taken and thus do not require any additional communication channel. The GSDC injects a subsynchronous current into the Chabei substation when the SSO occurs. The injection of subsynchronous currents essentially reshapes the impedance response of the wind farms connected to the Chabei substation and hence changing the whole system's impedance response. After validating the damping performance of the GSDC through CHIL tests, it was put into trial operation in 2015. The Guyuan system did not experience the unstable SSCI problem after that. Fig. 8 shows the developed GSDC

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hardware packaged into a standard cabinet (right) and the commissioning site of the Chabei substation (left).

The active power and subsynchronous dynamics of the system are recorded with and without adding GSDC. Fig. 9 displays the subsynchronous currents with and without GSDC. The plots show that the GSDC has efficiently damps the unstable SSO right after the SSCI occurs.

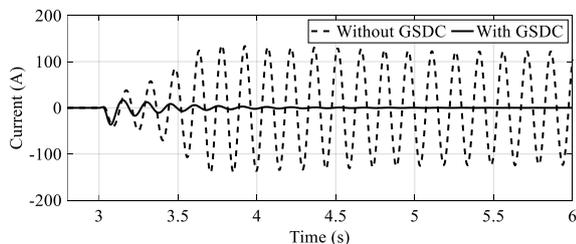Fig. 8 GSDC installed at Chabei substation in the Guyuan wind power system

Fig. 9 CHIL test results of GSDC subsynchronous current

5   SSCI analysis and mitigation guidelines

A step-wise procedure is suggested to investigate the SSCI in a practical wind power system. It involves the following steps:

Step 1: The first step is to collect the information about the system under study, including the generation and network topologies, and parameters of the system components, such as WTGs, transmission lines, HVDC lines, nearby steam turbine generators, transformers, etc.

Step 2: Next, obtain the upper and lower limits of normal operating conditions, such as wind speed, number of online WTGs, short-circuit ratio, series compensation, etc. If each distinct combination of the values considered as one operating condition, the total number of operating conditions would be nearly unlimited. In that case, it is almost impossible to model and analyse the system for all operating conditions, because the small-signal impedance model of the WTG has to be re-established for each operating condition. This is one of the issues yet to be addressed. The authors recommend intuitively narrowing down the total number of 'operating conditions' to form a set of critical evaluation conditions' by eliminating the safe operating conditions which do not pose the risk of SSCI.

Step 3: For each of the 'critical evaluation condition', construct a representative impedance network model according to the system topology and configuration

determined in Step 1. Convert the impedance-network model into lumped impedance to apply the quantitative reactance-frequency crossover' approach. If the system is stable, update the set of critical evaluation conditions' by excluding the studied combination of operating conditions.

Step 4: In the next step, construct a risk matrix, indicating the most critical to the least severe operating conditions and disturbances constituting the risk of SSCI.

Step 5: Finally, identify the stability or protection boundary and inform the system operator to design and implement a strategy to alleviate the instability risk.

Step 6: Based on the components participating in the interaction and comparisons of various possible mitigation measures, one or more suitable temporary, e.g., series capacitor bypass, e.g., generator- and/or grid-side impedance reshaping control solutions should be adopted for the stable operation of the target power system.

6   Conclusion

This paper overviewed the phenomenon, mechanism, and characteristics of the SSCI based on actual events reported around the world. The SSCI in renewable power generators threatens the stability of modern power systems with high penetration of converter-based renewable power generators. This paper discussed the practical impedance reshaping control techniques. The practical application cases of generator-side and grid-side impedance reshaping controls are presented. The field and test results presented in this research would boost up the confidence of practical application of these impedance reshaping controls. The grid-side control requires the oscillation frequency to be known beforehand. However, the oscillation frequency can be detected adaptively, and the controller parameters can also be updated online. Finally, a step-wise procedure is devised to investigate and mitigate the SSCI in a practical power system.

7   Acknowledgements

8   References

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