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TECHNICAL REPORT

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Dynamic characteristics of inverter-based resources in bulk power systems – Part 2: Sub- and super-synchronous control interactions

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DYNAMIC CHARACTERISTICS OF INVERTER-BASED RESOURCES IN BULK POWER SYSTEMS –

Part 2: Sub- and super-synchronous control interactions

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8A/99/DTR	8A/103/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

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A list of all parts in the IEC 63401 series, published under the general title *Dynamic characteristics of inverter-based resources in bulk power systems*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
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INTRODUCTION

Advancements in power electronic converters have led to an increased proportion of converter based renewable power generators in modern electric power systems. Power electronic converters use multi-time scale converter control structures to achieve smooth grid connection. Such control interactions cause oscillation with the frequency ranging from a few hertz to several kilohertz, which can interact with other converter-based devices or system components such as static compensators (STATCOM), series capacitors and weak AC grids. The interactions of converter control with series-compensated or weak AC grid cause oscillation in the subsynchronous and its complementary supper synchronous frequency ranges, named as sub- and super-synchronous control interaction or simply sub-synchronous control interaction (SSCI).

In the past decade, several incidents have been reported where wind turbine and photovoltaic (PV) converter controls interacted with series-compensated or weak AC grids at subsynchronous and/or supersynchronous frequencies. Post-event investigations have shown that the converter controls actively participate in these interactions. Unlike classical sub-synchronous resonance (SSR), SSCI is a system-wide phenomenon rather than a localized converter control issue. The mechanism and characteristics of SSCI are greatly influenced by converter control structures and parameters, generation resource intermittency, network topology change, grid strength, etc. Such factors distinguish the converter control participated interactions in converter-based generators from the classic SSR phenomenon associated with the conventional power generators. The oscillation caused by SSCI seriously threatens the stable and reliable operation of wind power systems.

Power systems with high-penetration of power electronic converters face a variety of oscillatory stability issues. Power electronic converter-based components such as converter-based wind turbine generators (WTGs), photovoltaic (PV), flexible AC transmission system (FACTS) and high voltage DC (HVDC) can interact with each other and/or with the series-compensated or weak AC networks. As a result of such interactions, oscillation from a few hertz to tens or hundreds of hertz could be triggered, as illustrated in Figure 1.

The interaction between doubly-fed induction generators (DFIGs) and series compensated transmission lines was first reported in the electric reliability council of Texas (ERCOT) wind power system in 2009. The frequency of triggered oscillation was 20 Hz to 30 Hz. Later on, from 2010 to 2016, frequent oscillation events were reported between DFIG and series-compensated network in the Guyuan system located in Hebei, China. In 2015, a new type of interaction was reported in the Hami wind power system in Western China. Post-event investigations showed that the full-scale converter (FSC) interacted with the weak AC grid causing strong sub- and super-synchronous oscillation. The frequency of oscillation originating from the FSC wind turbines matched with the shafts' natural frequencies of the nearby steam turbine generators, which resulted in intense torsional vibrations. In 2019, a power outage event in the UK's National Grid was also found to have been worsened by a 9 Hz oscillation. The converter controls of the FSCs in the Hornsea offshore wind farm participated in the event and amplified the negative resistance effect, which led to the sudden shutdown of the wind farm.

The frequency of oscillation triggered by the interactions between converter generators (e.g. wind or PV) and series-compensated or weak AC grid falls in the range of sub- and/or super-synchronous frequency. Due to the active participation of converter controls, the interaction is widely known as the subsynchronous 'control' interaction (SSCI). Note that although the frequency of the 2019 event in the UK's National Grid is below the system's synchronous frequency, careful consideration must be given before characterizing this event as an SSCI event.

Besides SSCI, several high-frequency resonance events have also been reported around the world. For example, the harmonic instability with frequency ranging from 100 Hz to 1 000 Hz in the Borwin1 offshore wind power project in the North Sea of Europe. In 2017, a high-frequency resonance was reported in the Yunnan grid after the Luxi project was put in operation. The high-frequency resonance occurred between the modular multilevel (MMC)-HVDC and the AC grid triggering the 1 272 Hz and its complementary frequency oscillation. Similar events involving

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interactions between converter-based devices and the grid have occurred around the world. The interaction phenomenon causing such high-frequency oscillation is widely known as high-frequency resonance or harmonic resonance.

This technical report aims at revisiting the existing terms and definitions, proposing benchmark models, modeling and analysis methods and mitigation schemes to better understand, analyze and control SSCI.

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DYNAMIC CHARACTERISTICS OF INVERTER-BASED RESOURCES IN BULK POWER SYSTEMS –

Part 2: Sub- and super-synchronous control interactions

1 Scope

Based on the interaction phenomenon and frequency range, this part of IEC 63401, which is a technical report, covers the "control interactions" in converter interfaced generators e.g, wind and PV with the frequency of the resulting oscillation below twice the system frequency. SSCI can be categorized into:

1) SSCI in DFIG is caused by the interaction between DFIG wind turbine converter controls and the series compensated network.
2) SSCI involving FSC (both type-4 wind turbine or PV generators) is caused by the interaction between wind turbine or solar PV's FSC controls and weak AC grid.

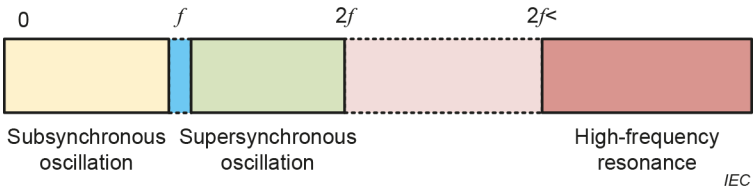

Figure 1 – Multi-frequency oscillations in the modern power system with high-share of renewables and power electronic converters

This technical report is organized into nine clauses. Clause 1 gives a brief introduction and highlights the scope of this document. Clause 4 presents the historical background of various types of subsynchronous oscillation (SSO) and revisits the terminologies, definitions, and classification in the context of classical SSR and emerging SSCI issues to better understand and classify the emerging interaction phenomena. Clause 5 provides the description, mechanism, and characteristics of the SSCI phenomenon in the framework of real-world incidents, including the SSCI events in the ERCOT, Guyuan, and Hami wind power systems. Clause 6 proposes two benchmark models to study the SSCI DFIG and FSC-based wind turbines or PV generators. Clause 7 gives an overview of existing and emerging modeling and stability analysis approaches to investigate the SSCI phenomenon. Clause 8 outlines various techniques to mitigate the SSCI. It discusses various SSCI mitigation schemes, such as bypassing the series capacitor, selective tripping of WTGs, generator, and plant-level damping control schemes. Clause 9 highlights the need for future works towards standardization of terms, definitions, classification, analysis methods, benchmark models, and mitigation methods.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

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4 Terms, definitions and classification

4.1 Existing terms, definitions and historical background

4.1.1 General

This subclause gives a brief overview of the historical developments to define and classify the subsynchronous oscillation issues in traditional power systems. Figure 2 shows a timeline of the classical SSR events and the historical development of terms and definitions related to SSR.

The formation of a series resonance circuit in induction generators in the presence of a series capacitor is not a new phenomenon. This series resonance phenomenon was first observed and named as the induction generator effect (IGE) in 1937 [1][1]. The resonance phenomenon related to the turbine's shaft emerged after the two consecutive resonance incidents that occurred in Mohave generating stations in 1970 and 1971 [2]. The Mohave incidents happened due to the excitation of the shaft's torsional modes, resulting in severe damage to the shafts of the turbo-generators. Post-incident studies on the Mohave incidents led to defining several terminologies for the first time, which have been reported in [3]. The concept of SSR, IGE, torsional interaction (TI) and torque amplification (TA) in a series compensated induction generator was presented. Until this time, SSR was thought to be triggered by the series capacitors in the transmission line. To harmonize the SSR research community, in 1976, a bibliographic report was published by the IEEE in which the work was classified into induction machine effect (IME) and torsional torque oscillation (TTOs) [4]. However, a few years later, another shaft failure event in the Navajo power station revealed that SSR can also be triggered by HVDC converters [5], [6]. Such a phenomenon was later named as the subsynchronous torsional interaction (SSTI) [5]. In an attempt to standardize and redefine the terms, in 1980, the IEEE SSR working group proposed standard definitions of the terms, such as SSR, IGE, TI, and TA to streamline the research community [7]. Subsequently, a second bibliographic supplement was published, which apart from the existing terms/definitions included a new term called device-dependent subsynchronous oscillation (DDSSO). The DDSSO was defined as the oscillation caused by power system devices, such as the power system stabilizers (PSSs) and static var compensators (SVCs) [8]. The SSR field tests at Square Butte showed that the HVDC system was involved in adverse interaction with the shaft of an adjacent turbine generator [9]. Subsequently, the second, third, and fourth supplements to the bibliographic report introduced a new classification in 1985, that is the DDSSO [4], [10], [11].

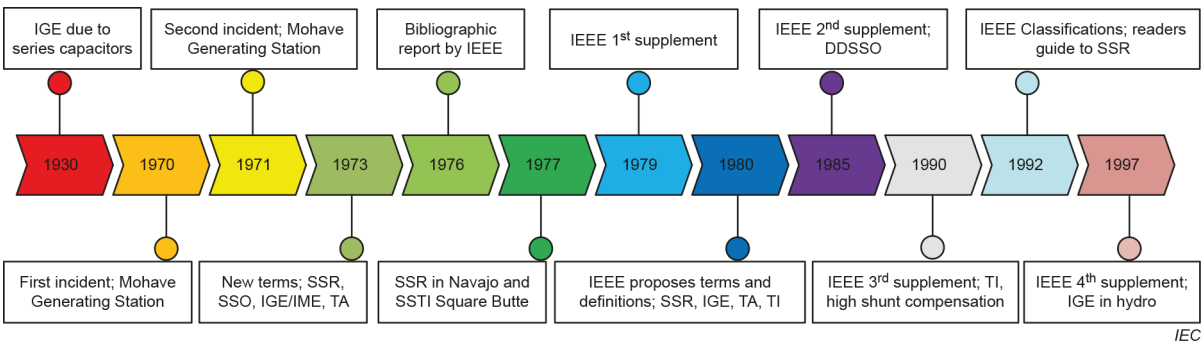

Figure 2 – Timeline of the historical developments of SSO terms, definitions and classification [12]

[1] Numbers in square brackets refer to the Bibliography.

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In 1992, the IEEE's working group put forward standard terms to define and classify the SSR issues in conventional turbo-generators [13]. The SSO was divided into SSR and DDSSO. The SSR was further divided into self-excitation (SE), IGE, TI, and shaft TA, as depicted in Figure 3.

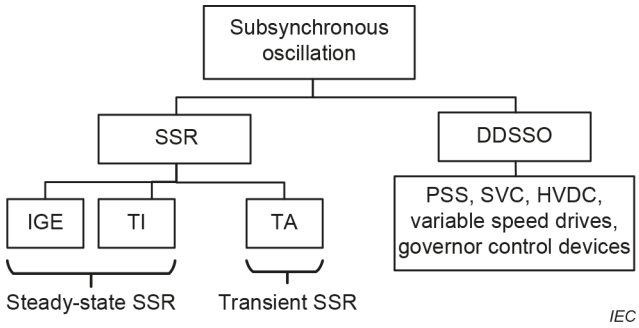

Figure 3 – Terms and classification of SSR by IEEE [13]

4.1.2 Subsynchronous resonance (SSR)

4.1.2.1 General

According to the IEEE definition of the term SSR [13], "it is an electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system".

The SSR is further divided into self-excitation (SE), also called steady-state SSR, and transient SSR to include TA. The steady-state SSR or SE covers the SSR caused by IGE and TI [13].

4.1.2.2 Induction generator effect (IGE)

SE of a series compensated induction generator is caused by the IGE, that is when the rotor circuits turn faster than the rotating magnetic field produced by the subsynchronous armature currents. Under this condition, the rotor resistance to subsynchronous current as viewed from the armature terminals becomes negative. The IGE occurs when this negative resistance is more than the sum of the armature and network resistance at a certain subsynchronous frequency [13].

4.1.2.3 Torsional interaction (TI)

TI is the interplay between the mechanical systems (turbine-generator) and a series compensated electrical network. The shaft of the turbine-generator responds to system disturbances at its natural frequencies and produces corresponding subsynchronous voltages at the generator terminals. If this subsynchronous frequency matches with the electrical resonance frequency of the network, the corresponding stator current induces a torque, which excites the torsional oscillations. Each time, the magnitude of the torque increases, resulting in growing oscillations [13].

4.1.2.4 Torque amplification (TA)

TA occurs following a large disturbance in a series capacitor compensated system. The system disturbance causes electromagnetic torque oscillation at the complement of the electrical network's natural frequency. If, somehow, this frequency aligns with one of the natural frequencies of the shaft, a resonance between the network's electrical and shaft's mechanical frequencies occurs [13].

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4.1.3 Device dependent SSO (DDSSO)

DDSSO is defined as the oscillation caused by the interaction between turbine generators and a wide range of fast-acting controllers of the power system components, such as HVDC converters, static VAR compensators, and high-speed governor controls.

4.2 Necessity to revisit the terms and classification

The mechanism and characteristics of the SSO associated with the WTGs are quite different from the previously reported conventional SSR events involving turbine generators. For example, the mechanism and characteristics of the interaction phenomenon depend on the structure and parameters of the wind turbine or PV's converter control, which actively participates in the interaction. Furthermore, the SSCI in converter-based generators is not just related to the converter controls; it is rather a system-level issue that is also influenced by other system-wide parameters. The parameters influencing the mechanism and features of the oscillation include wind speed, number of online WTGs, wind turbine converter controls, and their parameters, degree of series compensation, network topology, and stiffness of the AC grid. Another key difference is that the frequency coupling is sometimes very strong, which leads to a very large supersynchronous oscillation component in addition to the subsynchronous component. The frequency coupling effect is obvious in full-converter WTGs, in which sometimes, the magnitude of the supersynchronous oscillation is even larger than the subsynchronous oscillation. These characteristics are very different from the characteristics of SSR in turbo-generators. Thus, the terms, definitions, and classification should be redefined to better understand the mechanism of SSCI in WTGs.

4.3 Revisiting the terms and classification

4.3.1 General

It is recommended that the term "subsynchronous oscillation or SSO" should be used as a general term for an "oscillation" caused by any phenomenon that results in the "oscillation" with its frequency being within the sub-/super-synchronous range. Thus, the SSR, SSCI, IGE, TI, TA and DDSSO should be considered as "phenomena" whereas the "subsynchronous oscillation" as the cause of this phenomenon.

In an electric power system, the subsynchronous interaction phenomena can be better understood by categorizing the contributive system components into the "base" and "interactive" components [12], where

- Base components are the system components that are prone to be interacted by other system components present in the power system;
- Interactive components are the system components that have the potential to initiate or trigger the interaction.

Figure 4 shows a bunch of base and interactive components in a typical power system, that could potentially interact with each other and trigger oscillation in the range of sub-/ super-synchronous frequency. Based on the origin, the subsynchronous interactions can be classified into: 1) torsional interaction, 2) network resonance, and 3) control interaction, as illustrated in Figure 5. The revisited terms and classification are valid for the subsynchronous interaction in both conventional and renewable generations.

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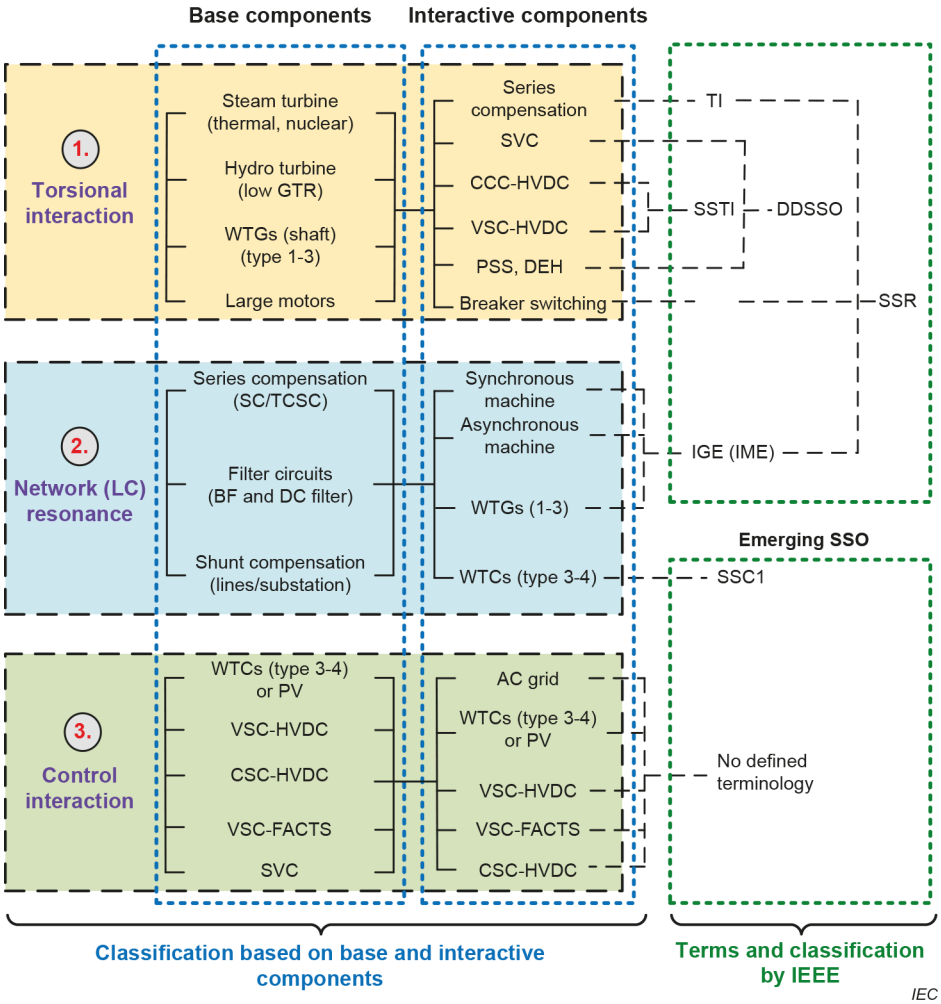

Figure 4 – Classification of subsynchronous interaction based on the origin [12]

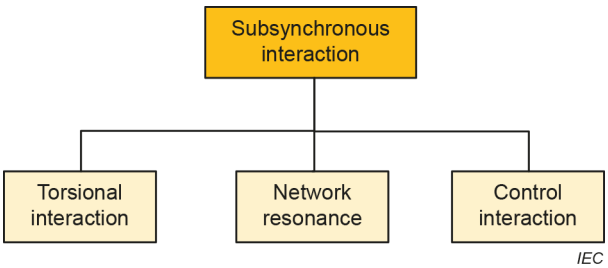

Figure 5 – Reclassification of subsynchronous interactions based on the interaction mechanism

4.3.2 Torsional interaction

The torsional interaction is defined as the interaction in which the mechanical dynamics of the generator shafts (either turbine generator or wind generators) interact with the converter controls of power electronic devices, such as the HVDC, and FACTS.

Referring to Figure 4, the torsional interaction can occur due to the interaction between the mechanical dynamics of any of the base components (such as traditional steam turbines, hydro turbines with low generator turbine ratio, type 1 to 3 wind turbines, and large motors) interact with any of the interactive components (such as fixed series compensation (SC), HVDC converter, FACTS converter, power system stabilizers (PSSs), governor controls, and breaker switching). This type of interaction covers all types of subsynchronous oscillations involving the

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shaft dynamics of conventional turbine generators as well as WTGs. It covers the shaft/torsional-related terms proposed in the IEEE's reader guide. The shaft or torsional dynamics terms by the IEEE are TI, TA, and SSTI.

The frequency of oscillation caused by the torsional interaction is in the range of subsynchronous frequency ($f_r<f_0$), where f_r is oscillation frequency and f_0 is the system's fundamental frequency.

4.3.3 Network resonance

The network resonance is defined as an electric power system condition where a series compensated electric network exchanges energy with the induction generators (either turbo or wind generators) at one or more of the natural frequencies of the combined system below the synchronous frequency. The definition is a modified form of the classical SSR definition.

The network resonance occurs between physically installed inductive (L) and capacitive (C) elements in the generation and transmission sides. The network resonance can also be called the L-C resonance. According to Figure 4, the base components include SC, thyristor-controlled series capacitor (TCSC), blocking filter (BF), DC filter, and shunt compensation. The base components can interact with any of the interactive components including synchronous machines, asynchronous machines, WTGs (type 1 to 3), and wind turbine converters (type 3 to 4). The L-C oscillation includes the oscillation phenomenon defined as IGE/IME in the IEEE's classification.

The frequency of oscillation caused by the network resonance lies in the range of subsynchronous frequency ($f_r<f_0$), where f_r is oscillation frequency and f_0 is the system's fundamental frequency.

4.3.4 Control interaction

The control interaction is the interaction between power electronic converter (PV or wind turbine converter) controls and series compensated or weak AC network. The converter controls in this type of interaction play a key role in defining the mechanism and characteristics of the oscillation.

The basic principle of this type of interaction is similar to the network resonance or L-C oscillation; except that the interaction is between virtual capacitance/inductance offered by power electronic converters controls instead of physical capacitive and inductive elements. According to Figure 4, the base components include wind turbine converters (type 3 to 4) or PV, voltage/current-source converter (VSC/CSC)-based HVDC, or FACTS) devices such as static series compensator (SSSC), static compensator (STATCOM). These base components could be interacted by the interactive components such as weak AC grid, wind turbine converters (type 3 to 4), VSC-HVDC, CSC-HVDC, and VSC-based FACTS controllers. This type of oscillation cannot be explained with IEEE's existing terms.

The frequency of oscillation caused by the control interaction lies in the range of subsynchronous and/or supersynchronous frequency ($f_r<f_0$ and/or $f_0<f_r<2f_0$), where f_r is oscillation frequency and f_0 is the system's fundamental frequency.

Besides the above three types of interaction phenomena, the network resonance, torsional interaction, and control interaction can exist simultaneously in a practical power system. The co-existence phenomenon has been observed in the recent real-world events in Guyuan and Hami wind power systems, for example:

- The network resonance and control interaction co-existed in the Guyuan incident. The SSO was triggered by the network resonance and sustained by the control interaction.

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- The control interaction and torsional interaction co-existed in the Hami wind power system. The oscillation was initiated by the control interaction and propagated through the grid, which caused the torsional interaction with the nearby turbo-generators.

4.4 Clause summary

The modern power system with high penetration of converter-based renewable power generators faces emerging instability challenges, including the SSCI in converter-based WTGs. The existing terms, definitions, and classification are revisited to accommodate the emerging oscillation issues as indicated by the historical background. In a proposed classification, the subsynchronous interactions are divided into 1) torsional interaction, 2) network or LC resonance, 3) control interaction based on the interaction phenomena.

5 SSCI incidents in real-world wind power systems

5.1 General

In the past decade, several SSCI incidents have occurred in wind power systems around the world [12]. The timeline in Figure 6 shows various SSCI events that occurred around the world. The first event occurred in the XcelEnergy wind power system in Minnesota, USA in 2007 [14], [15]. The incident occurred when the DFIG-wind farms were left in radial connection with the nearby series-compensated transmission line, increasing the net series compensation level. The event caused 9 Hz to 13 Hz SSO. In 2009, a similar SSCI event was observed in the ERCOT wind power system in Texas USA, which caused severe damage to the series capacitors and crowbar circuits [16] to [19]. It was also triggered when the DFIG-wind farms were left in radial connection with the series compensated network, increasing the net series compensation level. The 2009-ERCOT event caused 20 Hz to 30 Hz SSO. In 2011, a 4 Hz SSO event occurred due to the interaction between FSC wind turbines and low short circuit ratio (SCR) caused by the transmission outage in the same system in Texas, USA [20], [21]. From 2012 to 2016, several interactions have been reported in the Guyuan wind power system, causing 6 Hz to 9 Hz SSO [22], [23]. The SSCI occurred when power generated by the DFIG based wind power plant was very low. In 2014 and 2015, the SSCI occurred due to FSC wind turbines connected to the weak AC grid. The triggered SSO matched with nearby thermal power generators and triggered severe torsional oscillation. In 2017, the ERCOT wind power system in Texas faced several oscillation events due to the outage of transmission lines, leaving the wind farms in radial connection. The incidents have been replicated in [24]. In 2019, Great Britain's National Grid experienced a significant power outage [25]. The post-event investigations showed that the converter controls of the Hornsea's offshore FSC wind turbines participated in the event.

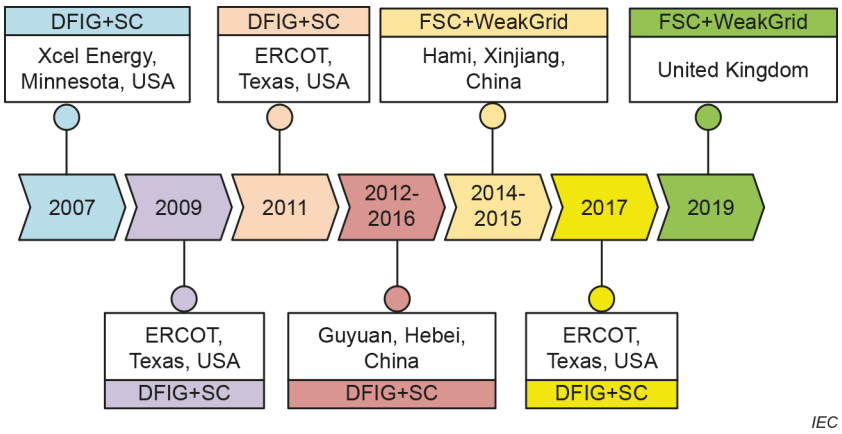

Figure 6 – Timeline of SSCI events reported around the world

The above events can be broadly organized into two types of interactions: 1) the interaction between DFIG and series compensated network, and 2) the interaction between FSC based generators (e.g. type-4 wind turbine and PV) and weak AC network. The active participation of

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wind turbine converter "controls" is the key to both types of interactions. Thus, they can be referred to as the "control interactions" or more precisely the "subsynchronous control interactions or SSCI". The "control interaction" can also be caused by the controls of other power electronic devices, such as FACTS and HVDC converters [26]. However, in this document, the term "SSCI" is used to describe the interaction phenomenon involving wind turbine or PV converter controls in the presence of either a series-compensated or weak AC grid. In the following subsections, the prominent real-world SSCI events in DFIG/FSC wind turbines and their mechanisms and characteristics are discussed.

5.2 SSCI in DFIGs connected to series-compensated networks

5.2.1 ERCOT SSCI incident in 2009

5.2.1.1 System description

At the time of the SSCI event, the South Texas transmission network consisted of two 50 % series compensated transmission lines connecting Lon Hill with Edinburg (LH-EB) and Nelson Sharpe with Rio Hondo (NS-RH), as shown in Figure 7. The wind power generated from the DFIG wind farms is fed into the grid through the Ajo substation, located at the middle of the NS-RH line.

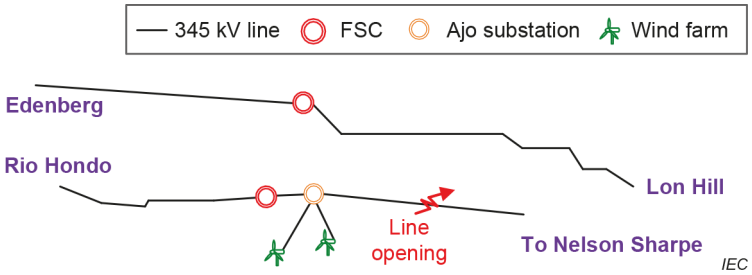

Figure 7 – Structure of the ERCOT wind power system in 2009 [16]

5.2.1.2 Event details

In 2009, an SSCI event occurred when the 345 kV Ajo-LH line was tripped due to a line to ground fault, which eventually left the wind farms in radial connection with the rest of the South Texas grid [16]. The tripping of the AJ-LH line resulted in a sudden increase in the degree of series compensation from 50 % to 75 %, which quickly triggered the oscillation with the oscillation frequency of around 20 Hz to 30 Hz. The recorded current and voltage waveforms are shown in Figure 8. It can be observed that the amplitude of oscillation increased quickly. The post-fault analysis showed that at subsynchronous frequencies, the rotor's negative resistance significantly increased by the participation of WTG's converter controls as seen from the stator terminals. The interaction was indeed triggered by the active participation of the wind turbine converter counters.

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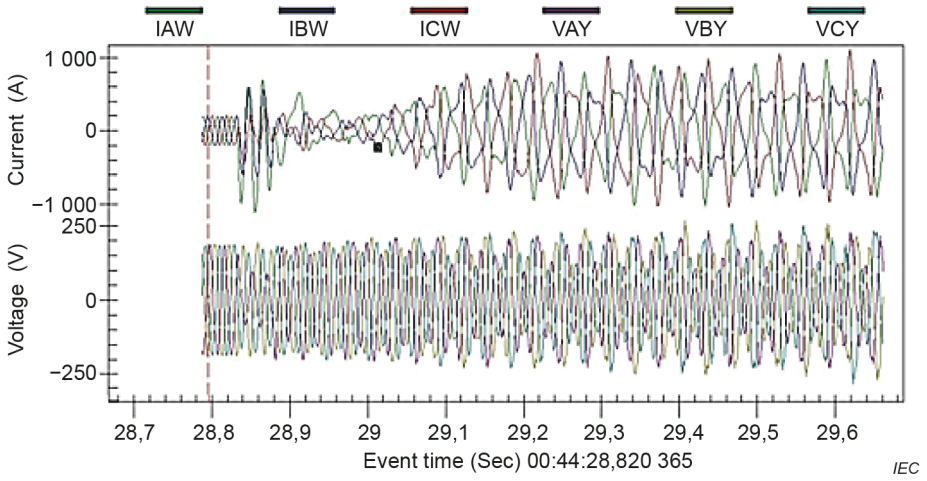

Figure 8 – Oscilloscope record of the 2009 SSCI event in the ERCOT system [19]

5.2.1.3 Consequences

The initiation and build-up process of the oscillation caused by the SSCI was very fast. The amplitude of the system voltages increased to 150 % within 150 ms. The sudden increase in current and voltages damaged the series capacitors and the DFIG's crowbar circuits [19].

5.2.2 ERCOT SSCI events in 2017

5.2.2.1 System description

The one-line diagram of the relevant part of the ERCOT system in 2017 is shown in Figure 9. There are a total of six DFIG-based farms connected with the Lon-Hill Edinburg (LH-EB) 345kV line. Two of the wind farms are connected at substation 3, two at substation 4, and two at substation 5. The transmission line section connecting substations 3 and 4 consists of two series capacitor banks at both ends. It is obvious from the system topology that tripping of the transmission line from either side of the wind power plants would leave the wind farms radially connected to the rest of the network, as shown in Figure 9. In 2017, three SSCI events were detected, which were triggered by the transmission line outages.

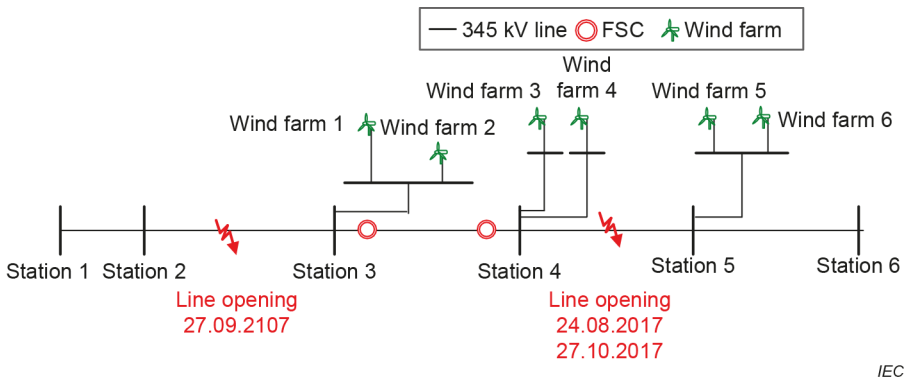

Figure 9 – Structure of the ERCOT wind power system in 2017 [24]

5.2.2.2 Event details and consequences

In 2017, three SSCI events were recorded in the ERCOT system in three months [24].

Event#1: The first SSCI event was detected on August 24, 2017. The SSCI was triggered when the 345kV transmission line section connecting substations 4 and 5 tripped due to a transmission line fault. After the 2009 event, the ERCOT system was equipped with an

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appropriate protection system to detect the oscillation. Thus, the series capacitors were bypassed automatically when the oscillation was detected by the protection system, which saved the capacitors from being damaged. Twenty minutes later, the series capacitors were brought into service manually. However, the SSCI triggered again and the magnitude of the oscillation increased rapidly. The recorded current and voltage waveforms along with the frequency spectrum before and after the capacitor reinsertion are shown in Figure 10. The oscillation disappeared after the series capacitor was bypassed.

Event#2: The second SSCI event was recorded on September 24, 2017. A line-to-ground fault between substations 2 and 3 left the wind farms 1 and 2 to operate with the two series capacitors, as indicated in Figure 9. The diverging oscillation suddenly appeared in the current signal. Consequently, wind farms 1 and 2 were tripped within 24 cycles, by the differential protection relay of the step-up transformer. The recorded current and voltage waveforms are shown in Figure 11.

Event#3: The third SSCI event was observed on October 27, 2017. In this event, a line to ground fault between substations 4 and 5. The line opening caused the wind farms 3 and 4 to operate with the two series capacitors installed between the substation 3 and 4. Compared to the August 24 event, a less intense oscillation was excited. The oscillation disappeared after the faulty line section was manually restored within three minutes. The SSCI event was less severe and the series capacitors were not damaged, nor the wind power plants tripped. The recorded current, voltage, and frequency spectrum are given in Figure 12.

In all three events, the SSCI occurred when the wind power plants formed a radial connection with the series capacitors. The frequency of the resulting oscillation remained within the subsynchronous frequency range 20 Hz to 30 Hz. The magnitude of the corresponding supersynchronous frequency components was negligible in all three events.

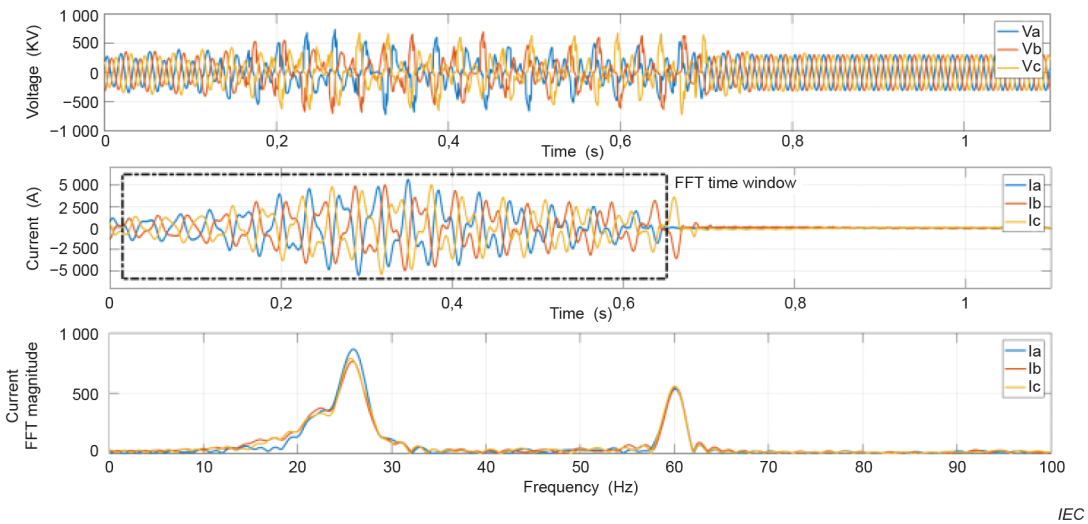

Figure 10 – Event#1 August 24, 2017: current, voltage and frequency spectrum of the current during the SSCI event and after bypassing the series capacitor [24]

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