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Protection and Control of Modern Power Systems

REVIEW **Open Access**

Review of sub-synchronous interaction in wind integrated power systems: classification, challenges, and mitigation techniques

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Abstract

Emerging sub-synchronous interactions (SSI) in wind-integrated power systems have added intense attention after numerous incidents in the US and China due to the involvement of series compensated transmission lines and power electronics devices. SSI phenomenon occurs when two power system elements exchange energy below the synchronous frequency. SSI phenomenon related to wind power plants is one of the most significant challenges to maintaining stability, while SSI phenomenon in practical wind farms, which has been observed recently, has not yet been described on the source of conventional SSI literature. This paper first explains the traditional development of SSI and its classification as given by the IEEE, and then it proposes a classification of SSI according to the current research status, reviews several mitigation techniques and challenges, and discusses analysis techniques for SSI. The paper also describes the effect of the active damping controllers, control scheme parameters, degree of series compensation, and various techniques used in wind power plants (WPPs). In particular, a supplementary damping controller with converter controllers in Doubly Fed Induction Generator based WPPs is briefly pronounced. This paper provides a realistic viewpoint and a potential outlook for the readers to properly deal with SSI and its mitigation techniques, which can help power engineers for the planning, economical operation, and future expansion of sustainable development.

Keywords Damping controller, Doubly fed induction generator (DFIG), Series compensations, Sub-synchronous interactions (SSI), Sub-synchronous resonance (SSR)

1 Introduction

In order to meet the enormous electricity demand, renewable energy sources are aiding in the current power system. Wind energy is one of the leading renewable sources, and it is projected that if all countries were to build wind farms on 2% of their land area, their energy needs could be met [1, 2]. Wind energy resources are free of cost provided by nature, are abundant and eco-friendly, while the only cost is the conversion of energy [3]. With so many different technologies available, the DFIG-based wind energy conversion system stands out because of its variable speed operation, ability to operate in both sub-synchronous and super-synchronous modes, low cost, and high power density [4].

1.1 Background

Electricity generated from wind energy can easily be integrated into the existing power grid either by commissioning new dedicated transmission lines or improving existing transmission lines' power transfer

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capacity [5]. Instead of commissioning a new transmission system, existing transmission networks can be used by installing high voltage DC (HVDC) and flexible AC transmission system (FACTS) technologies and series capacitors which improve the effective reactance of the network resulting in high power transfer capability from the power grid to utilities [6–9]. In this context, it can be assumed that power electronic converters will dominate future power systems on both generation and transmission sides. Connecting wind turbines in the power system creates new challenges for the system's stability, e.g., super and sub-synchronous oscillations [10], which are originated due to the series compensated line and power converter-dominated power system [11]. The underlying causes of oscillation have been discovered to be the sub-synchronous interaction (SSI) of a typical turbo-generator mechanical shaft system with series compensated (SC) transmission lines or fast control devices like FACTS, HVDC controllers, and power system stabilizers (PSSs) [12–15]. If suitable preventive actions were not quickly implemented, SSI could result in one or more subsequent consequences [16, 17]:

(i) *Equipment damage:* Voltage overshoots can occur in SSI in such a way that in milliseconds, the voltage tends to reach the overvoltage pick-up value of a relay. For transient overshoots, the protective relay will not isolate the feeder instantaneously. Consequently, the transient overvoltage generated may damage the equipment [18, 19].
(ii) *Power generation loss:* Due to unstable oscillating overshoots of voltage at the point of common coupling, wind turbine generators (WTGs), wind farms, and conventional generating power stations may trip, and the total power generated will thus be reduced [20]. This can lead to financial as well as asset loss for the organization [21, 22]. From a historical event, it is evident that in Guyana (in China), the power was reduced from 219 to 75 MW due to a typical SSI event. Similar events occurred in the Hami wind power system, where a 600 MW steam turbine was tripped by torsional relays due to SSI. Since SSI introduces harmonics in the system, it degrades the power profile of a system. The oscillating voltage can also lead to various equipment damage installed in wind energy systems.
(iii) *Power quality:* Another observable effect is that SSI brings subharmonic and inter-harmonic components, therefore degrading the power quality and imperiling the performance of installed equipment. For example, the inter-harmonic currents develop a loud noise and derate the efficiency of transformers [23, 24].

1.2 Motivation

This form of SSI phenomenon seen in wind farms has become a significant challenge in preserving modern power systems' stability and efficiency [25, 26]. It can cause damage to the vital equipment used in power systems and reduce the power generation capability of generators. The power quality of such a system will also degrade if appropriate preventive measures are not taken [18, 23, 27]. Therefore, there is an urgent need to establish realistic mitigation strategies for SSI to ensure grid-interfaced wind farms' smooth and efficient operation.

1.3 The need for review based on literature challenges

With series compensated transmission lines, the first two events were reported at Mohave Generating Station in Southern Nevada in 1970 and 1971 [28]. The first DFIG-based wind power generation incident occurred in 2007 in Minnesota and then later in October 2009 at the Zorillo Gulf Wind Farm in Texas due to an interaction with SC transmission lines. Subsequent incidents occurred in December 2012 and 2015 in Guyuan and Hami wind power grids in China, respectively, without the use of series compensation [21, 27, 29, 30]. WTGs lead to a more complicated form of sub-synchronous oscillations (SSO) than traditional turbo-generators in this regard. For example, in an installed wind power plant (WPP), SSI can happen without a series compensated transmission line. The emergent SSI phenomena found in practical WPPs are relatively new and cannot be appropriately interpreted with the available existing literature. The timeliness of the state-of-the-art review paper on SSI are shown in Table 1.

As per existing literature, classification of SSI is based on DFIG and traditional generators, which is unable to cover other emerging types of low frequency oscillations [29, 31]. SSO was reclassified in [37], but it was done in a highly complex way and did not cover a large scale of wind farms. Reference [32] classified SSO as inductor-capacitor (L-C), torsional, and converter-grid type oscillations but did not explain the triggering mechanisms or explain different characteristics of SSI problems associated with WPPs. Therefore, reclassification of the SSI phenomenon is required to understand the problems in wind farms. This study first describes the historical evolution of SSI concepts and IEEE classification, followed by an analysis of recent incidents in practical WPPs due to SSI. Subsequently, new terminology and classification of SSI are proposed to provide a better understanding of all forms of sub-synchronous frequency interactions for the overall power system with renewable energy integrated/hybrid power systems.

Table 1 Timeliness of the state-of-the-art review paper on SSI

Exiting Literature		Contribution
Ref	year	
[33]	2013	This work has addressed SSR in WPPs, comprising modeling, analysis the effect of control parameters, and mitigation techniques. The study focused on variable wind turbines
[34]	2016	This paper analyzed SSR, control as well torsional interactions in all types of wind farms and reviewed few mitigation techniques for the same
[35]	2018	This paper reviewed SSR analysis and its mitigation in DFIG-based WPPs
[36]	2018	This paper provided new terminology and classification for SSO of a large-scale wind power system and discussed some practical event due to SSO
[37]	2019	This paper reviewed the mitigation techniques of sub-synchronous control interactions in WPPs at different stages, for instance, planning, operation scheduling, active damping controlling, and emergency stage, and discussed the associated challenges
[38]	2019	This paper analyzed the Induction generator effect (IGE) and sub-synchronous control interactions in DFIG and PMSG-based WPPs and discussed the typical analysis and some mitigation techniques for the same
[39]	2020	Various SSO types were assessed in this paper based on the way they interact. Additionally, the mitigation strategies for the aforementioned SSO were provided
[40]	2020	This paper reviewed the emerging SSO due to the interactions between DFIG and series compensation, the interaction between weak grid and voltage source converter. A few mitigation techniques for SSO were also reviewed
[41]	2021	The SSO phenomenon has been examined in this study to categorize the current SSO phenomenon by integrating the interaction between a DFIG and converter under sub-synchronous torsional interaction, taking wind and hydropower applications into consideration
[42]	2021	This paper reviewed the oscillations in DFIG based WPP due to SSR and ferro resonance
[43]	2021	This research paper examines the modeling and stability analysis techniques used for sub-synchronous control interactions investigations in large-scale wind farms. It draws attention to the benefits and drawbacks of various modeling techniques and analysis standards
[44]	2022	This paper reviewed the mitigation techniques of SSR and high frequency resonance in a DFIG based WPP connected to weak grid
[45]	2022	This study reviewed actual SSO occurrences in practical power systems over the last decades
This Work		This study proposes new terminology and classification for SSI as per the current research status.. The timeliness of practical events that occurred in power systems due to SSI till now are reviewed, and mitigation techniques are suggested for the practical power systems as per the existing literature. The analysis techniques for SSI are also reviewed in this paper

1.4 Scope of work

The theoretical architecture of SSI mitigation scheme has gained a great deal of publicity over the last decade. Many SSI mitigation techniques, including sensing and isolating the FACTS-based damping controls [17, 23], wind turbine converter (WTC) control modifications, and controlled series compensation, have been documented [31, 32]. The key focus of this paper is to review the supplementary damping control (SDC) for converter control of DFIG-based WPPs. The review is supported by the restrictions and challenges inherent in different techniques in the existing installed systems.

1.5 Contribution of this literature review

The followings are the key contributions of this review paper:

- A brief report on the historical development of IEEE terminologies of SSI and its classification with a timeline along with other emerging terminologies.
- Proposing a new classification based on the interaction mechanism between different power system elements in recent events that occurred in existing installed wind farms.
- A brief discussion on the SSI analysis techniques, supported by advantages and limitations.
- Summarizing practical incidents thatoccurred due to SSI according to the proposed terminologies and classifications.
- A brief discussion on the solution techniques, supported by restrictions and challenges associated with executing different solution techniques on a practical framework.

1.6 Paper Structure

The rest of the sections are structured as follows. The history of IEEE terms and classifications for SSI are presented in Sect. 2, while Sect. 3 offers the proposed terms, their classifications, and historical events in practical systems. An investigation of the analysis techniques for SSI is presented in Sect. 4, and Sect. 5 elaborates on the solution techniques and their challenges. Section 6 discusses detailed future trends, open challenges, recommendations, and overview of the research. Finally, Sect. 7 presents the conclusions of the paper.

2 IEEE Standard terms for SSI and its classification

2.1 History of IEEE standards terminology

Earlier in the 1930s, synchronous machines were found to act as an induction machine due to a series capacitor's participation that generates a sub-synchronous current [46]. Later this occurrence is referred to as the induction generator effect (IGE), and an incident occurred at the Mohave power station in Southern Nevada in 1970 [28] due to the interaction of the electromechanical devices and the involvement of the series capacitor during which the generator shaft was seriously damaged. Later, the name was referred to as torsional interaction (TI), while another incident occurred in 1971 at the same generator power station [47]. Following the two consecutive incidents, this topic gained serious attentions on terms such as IGE, TI, torque amplification (TA), and SSR, which were debated in 1973 [48]. Besides, some researchers concluded that the above phenomenon occurred due to the SC transmission lines and minimizing damping torsional vibrations, which resulted in SSR participation [49]. Later, an IEEE committee was created, and a report on SSR studies was published in 1976 [50]. A square Butte HVDC test was conducted in USA in 1977, and the results revealed that HVDC converters could also introduce adverse sub-synchronous frequency interactions with turbine generators, which is now known as sub-synchronous torsional interactions (SSTI) [51]. Following these incidents, researchers have been focusing their efforts on reducing SSR and SSTI due to SC transmission lines and the involvement of power converters [52, 53].

In its first bibliographic appendix published in 1979, an IEEE working committee summarized the SSR literature and categorized SSR into IGE and torsional oscillations [54]. To unify academia and industry on the SSR issue, standard IEEE terminologies and SSR definitions were proposed in 1980. It further categorized SSR into IGE, TI, and TA, and provided a standard definition of each terminology. In 1985, the second bibliographic supplement introduced device-dependent sub-synchronous oscillations (DDSSO), a concept that covered a wide variety of control devices [55]. This effect was found during the commissioning stage of Ontranio hydro units in 1985 [56]. The third bibliographic supplement published in 1990, claimed that SSR events could occur due to a transmission line with high shunt compensation [50]. An IEEE committee gave a standard classification and definition for SSR and countermeasure techniques in 1992 [57]. SSI between hydro turbines and SC transmission lines was started in the fourth bibliographic supplement published in 1997 [58]. The timeline in Fig. 1 summarizes a brief overview of the evolution of SSO terminologies.

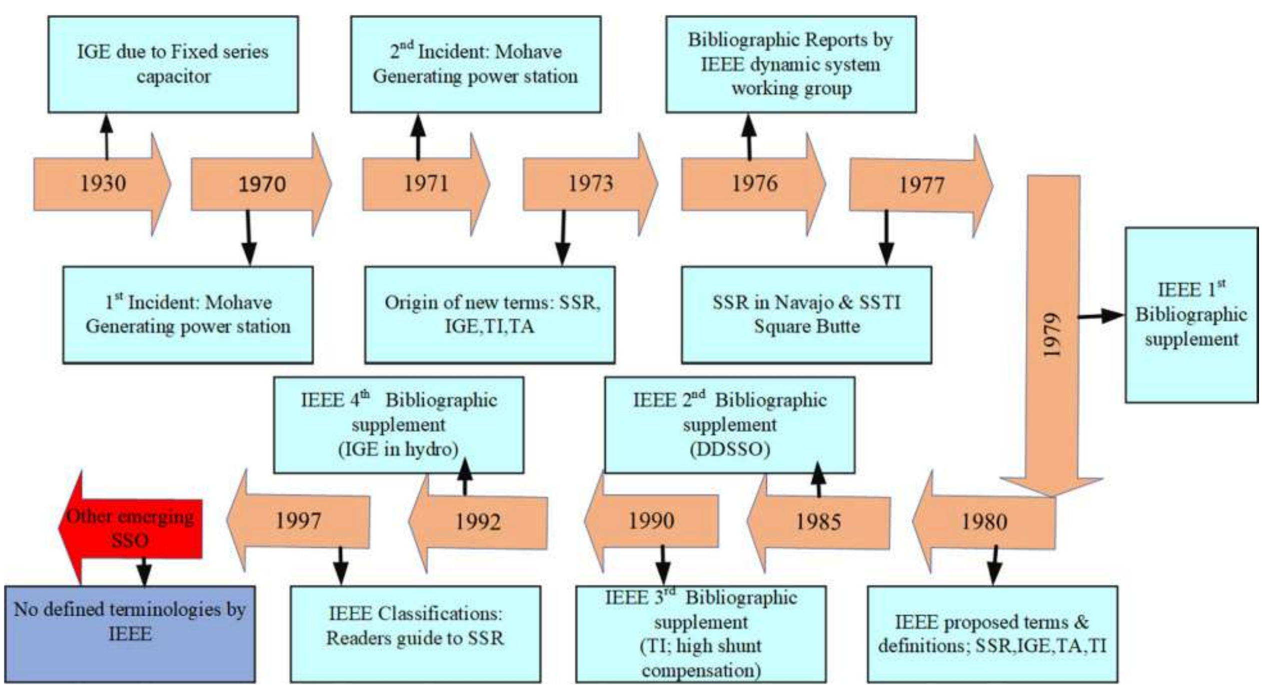


Fig. 1 Summary of evolution for traditional SSO terminology

2.2 IEEE's classifications

"Sub-Synchronous Resonance Working Group of the System Dynamic Performance Subcommittee" presented standard terminologies, definitions, and classifications after many attempts [59].

SSR and DDSSO come into the SSO phenomenon, as shown in Fig. 2. During the SSR phenomenon, there must be involvement of series compensated transmission lines, whereas in DDSSO, there are participation of fast control devices, i.e., HVDC, SVCs, PSSs, governor control, and variable speed drives [49]. Thus, SSO is classified into SSR and DDSSO as fallows.

2.2.1 Sub-synchronous resonance (SSR)

SSR is prompted by SC transmission lines connected through a turbine-generator mechanism and exchanges energy at a frequency below the fundamental frequency [60]. Due to the series capacitor, a resonance condition appears in a system as an L-C circuit [61], and the resonance frequency can be calculated as:

$$f_{er} = f_s\sqrt{\frac{Xc}{Xl}} \tag{1}$$

where f_s is the synchronous frequency or fundamental frequency, Xc is the reactance of the series-connected capacitor, and Xl is the total reactance available in the system, including the generator, transmission line, and transformer of the system. The positive sequence current of the armature current at resonant frequency f_{er} produces a stator flux, and the rotor winding induces voltage, resulting in a current at a frequency of $f_r = f_0 - f_{er}$, where f_0 is the rotor frequency generated due to its rotation. These currents, which may maintain sub-synchronous armature currents, are generated in the rotor as a result of sub-synchronous stator voltage at sub-synchronous frequency [62]. The sub-synchronous frequency current, however, results in a torque that dampens negatively. Sub-synchronous currents' negative dampening impact can eventually cause the generator shaft to fail.

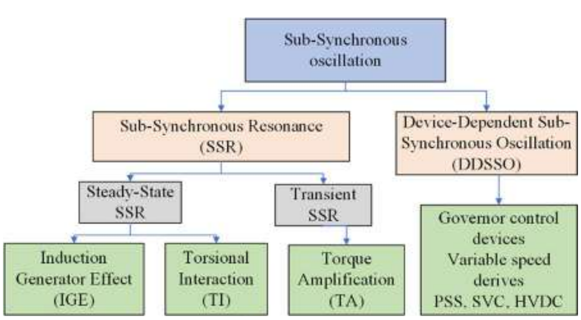


Fig. 2 Classification of SSO by IEEE

The IEEE categorizes SSRs into two categories at the outset: (i) Steady state; and (ii) Transient state, also known as torque amplification.

2.2.1.1 Steady state Steady state comprises Torsional Interactions and Induction Generator Effect.

(i) *Induction generator effect* Induction Generator Effect is only caused due to available electrical machines in the network, while it does not involve a generator-turbine mechanism. The series capacitor compensated system is excited due to the induction generator effect. The rigid rotor is responsible for the induction generator effect caused in the system, and the synchronous generator acts as an induction machine for a sub-synchronously rotating stator flux due to resonance in the circuit. The slip at a sub-synchronous frequency can be defined as [59, 63]:

$$S_{SSR} = \left(f_{er} - \frac{f_0}{f_{er}}\right) \tag{2}$$

The equivalent rotor resistance at a sub-synchronous frequency is:

$$R_{eq} = \frac{R}{S_{SSR}} \tag{3}$$

If $f_{er} < f_0$, the resistance becomes negative, reflecting that the damping is negative, and an over-damped oscillation of voltage and current would be observed [59].

(ii) *Torsional interactions* Synchronous generator rotor produces oscillation frequency f_{en} due to torsional frequency f_n, which is responsible for generating armature voltage at sub-synchronous frequency range. The oscillating frequency is $f_{en} = f_0 - f_n$. If this voltage component frequency (f_{en}) matches the system's electrical resonating frequency, the electromagnetic torque produced will enhance the torsional oscillation, which reflects in the mechanical system [64]. Generally, the torsional oscillation is close to the electrical resonant frequency.

As same as IGE, TI also guides the self-excitation of the generator at sub-synchronous frequencies. Torsional oscillation is developed because of electrical and mechanical systems' interaction at a specific frequency, whereas IGE is a purely electrical phenomenon and doesn't depend on mechanical systems.

2.2.1.2 Torque amplification The transient electric torque is developed on the generator rotor due to a significant disturbance in the network [65]. These transient electrical torques oscillate, and some components include sub-synchronous torques. The sub-synchronous torque oscillates when the frequency is close to the mechanical system's torsional frequency. This has be referred to as torque amplification [64].

2.2.2 Device-dependent sub-synchronous oscillations

Sub-synchronous oscillations in turbine generators are caused by interactions with other parts of the power system in addition to interactions between turbo-generator set and series capacitor compensated networks. PSSs, HVDC converter controls, SVC, controls for high-speed governors and converters for variable speed drives, are further potential sources [66]. Possible sources for the excitation of SSO can be any devices that regulate/reacts quickly to power/speed fluctuations in the sub-synchronous frequency range [57]. For instance, PSS dampens oscillations in the power system at low frequencies. The parameters of PSS and feedback signals, which have one or more oscillatory signals corresponding to the natural torsional modes of the shaft system, may be injected into the generator field windings. As a result, the torsional modes may be excited into SSO. Similarly, the HVDC converter and a governor control action can also excite SSO [38].

2.3 Other emerging terminologies

The penetration of renewable energy is increasing, and the development of power electronic devices plays a vital role in improving the efficiency and performance [67, 68]. However, due to the involvement of power electronic devices, the complexity of the power system is increased [69]. Since presenting standard classifications, terminologies, and definitions in 1992, the IEEE working committee has not addressed the most recent developments in this field.

Power electronics converters tend to have fast control mechanism which causes oscillations in the sub-synchronous frequency range [16]. An incident occurred in 2009 in ERCOT, as introduced by the named sub-synchronous control interaction (SSCI), was an interaction between wind turbines and an SC transmission line [29]. The term SSCI was considered for the issues related to series compensated lines and wind turbines [70]. As per IEEE's classifications and terminologies, it does not have a clear insight into the oscillations' dominant source. A classification was proposed to comprise all the issues and future probability of interactions in both turbo-generator and wind turbine at the sub-synchronous frequency range, in which SSO was divided into three major parts: (i) inductor-capacitor (L-C); (ii) Torsional oscillations; and (iii) converter-grid type oscillations [36]. These classifications become more complex, and neither provide a dominant reason behind the oscillations nor cover all the future probability of interaction in a simplified way. In [35], classification was done based on conventional turbine generators and wind power system SSR, while in some further studies [60], the SSI term was used instead of SSO. However, there is no existing standard classification and terminology found in this review which can guide new researchers in dealing with SSI associated with the power system [71].

3 Proposed classification of SSI

This section proposes a new classification along with previous IEEE standards [57]. Extending classification to get more defined knowledge of the emerging SSO phenomenon and covering all types of interactions in the conventional and renewable power system have been done precisely and efficiently. In the proposed classification, DDSSO is classified into sub-synchronous torsional control interactions (SSTCI) and sub-synchronous converter control interactions (SSCCI). As DDSSO individually cannot define the dominant source of interaction, while as the name suggests, SSTCI shows the interaction between turbo-generator and control devices or any FACTS devices. In contrast, the name SSCCI suggests that interaction is between converter control and series compensated line/FACTS control devices [72]. The detailed classification of an entire sub-synchronous phenomenon is shown in Fig. 3 and discussed in detail.

Generally, SSI refers to energy exchange between two systems at natural frequencies below the fundamental frequency. In an electrical system, many elements are involved, such as generator's mechanical shaft, capacitor, reactor for reactive power compensation, and various control equipment used to optimize the power utilization. Based on these elements, SSI can be further classified into SSR, SSCCI, and SSTCI.

3.1 Sub-synchronous resonance (SSR)

As described in Sect. 2.2.1, SSR exchanges energy at a frequency lower than the fundamental frequency and is triggered by SC transmission lines connected via a turbine-generator mechanism [60]. Due to the series capacitor, a resonance condition appears in a system [61]. As mentioned earlier, an SSR is produced due to the interaction of stator flux with rotor flux at a frequency f_0, and the torque is developed at the frequency of $f_r = f_0 - f_{er}$. If the developed torque frequency f_r matches the natural frequency of the mechanical generator-shaft combination, torsional stress is developed in the shaft, and an undamped oscillation will be produced, leading to the failure of the mechanical systems [73, 74].

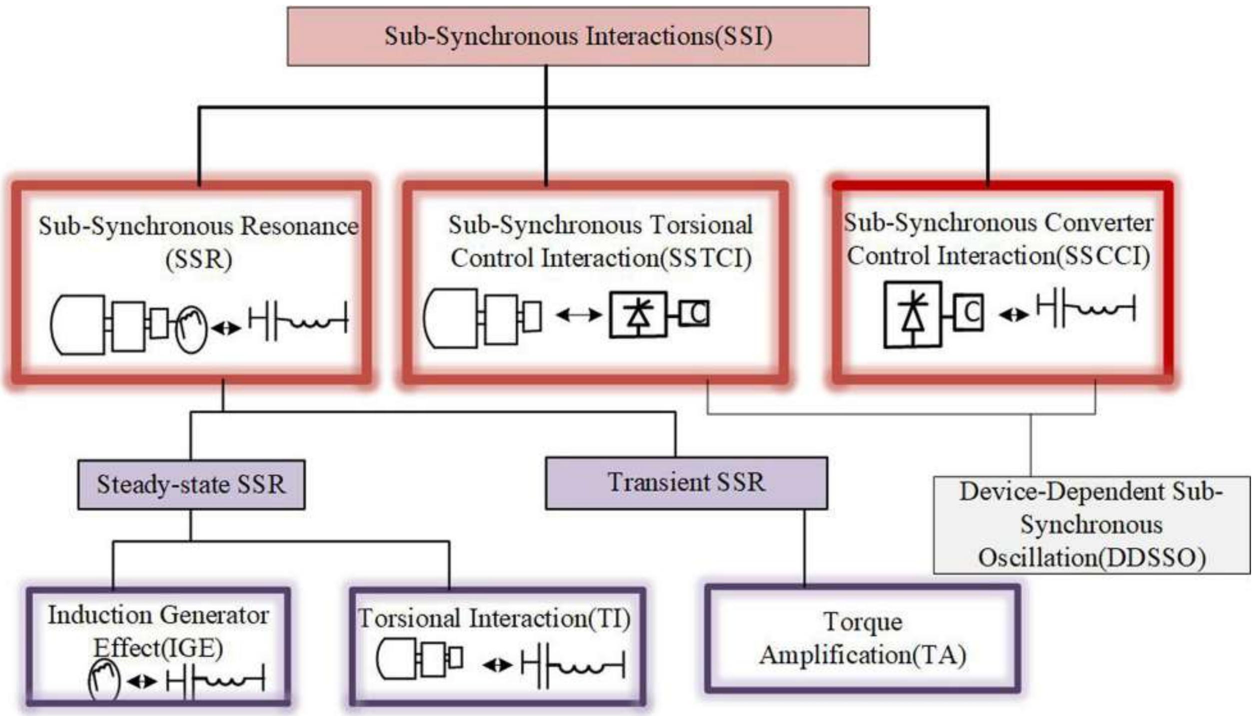


Fig. 3 Proposed classification of SSI

The conventional SSR occurs in a synchronous machine of thermal power plant, transmission line associated with series capacitance, wind energy system under certain circumstances. SSR may further be divided as due to Induction Generator Effect and Torsional Interaction [57]. The further classification of SSR is the same as the classification proposed by the IEEE, which has already been discuss in Sect. 2. The current research status of SSR is focusing on SSR analysis techniques and mitigation techniques, which will be discussed in Sects. 4 and 5, respectively.

3.2 Sub-synchronous converter control interaction

SSCCI refers to interaction between the power electronics converter control circuits and SC line. The resonance frequency is not fixed in SSCCI, which depends upon a particular situation of the converter control algorithm [13]. It is of utmost necessity to control these oscillations, which can build up drastically because of converter control and a pure electrical network. The control system associated with the wind turbines' converter generates a negative resistance under SSR [52]. A power electronic circuit produces multiple slip frequencies caused by switching of rotor current, and a negative resistance is generated, which is responsible for the undamped oscillation produced in the network [75]. However, SSCCI is a multi-variable dependent phenomenon, making it challenging to forecast any relationship.

There have been many incidents occurred due to the involvement of wind turbine converter control and series compensated transmission line/weak grid. The timeline of the practical events is shown in Fig. 4 due to SSCCI phenomenon. A 100 MW DFIG-based WPP that was accidentally left radially linked to a 345 kV series-compensated transmission line in south central Minnesota in 2007, was the first SSCCI event resulting in SSO around 9–13 Hz [29, 45]. In 2009, a similar incident took place in Texas, which harmed the series capacitor and crowbar circuits. A DFIG-based WPP was connected with a 50–70% fixed SC transmission line, and SSCCI was triggered at 22 Hz causing the current and voltage to increase very quickly up to 300% in 0.4 s, resulted in the damage of the series capacitor in 0.2 s [76]. Oscillations around 4 Hz were observed at a PMSG based WPP in Texas (2011) region after a transmission line was tripped [19, 77–80]. Between 2012 and 2016, the Guyuan wind power system experienced several SSCCI occurrences. More than 58 oscillation incidents with oscillation frequencies between 6–9 Hz were observed in 2012 in Guyuan grids, where DFIG-based WPP having double circuits of series compensated transmission lines connected to Guyuan station with Inner Mongolia and North China grids [27, 81].

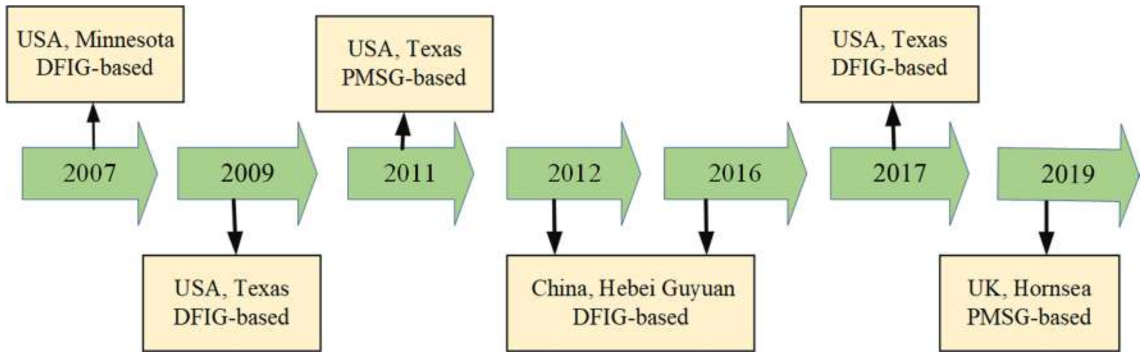


Fig. 4 Timeline of reported SSCCI events due to involvement of WPP and series compensated transmission line/weak grids

In 2016, in a 600 MW DFIG-based WPP in Northwest China (300 turbines of 2 MW), instantaneous voltages and currents were found to oscillate at frequencies of 37 Hz and 63 Hz [82]. The oscillations were eliminated by strengthening the grid (a second 500 kV line was built and placed into service) and updating the WPP converter control [41]. For the Texas ERCOT wind farm in 2017, SSCCI occurrences were documented. The instantaneous current frequency range is 22–26 Hz, and by updating the WPP converter control software, WPP vendors resolved the problem [83]. The interaction of the DFIG control system and a SC line was the cause of all the aforementioned events. The majority of incidents were caused by a transmission line failure, which left the wind farm radially connected to a series compensated line. Ten minutes prior to the interruption of the Great Britain (GB) power grid (Hornsea) in August 2019, oscillations with a frequency of 9 Hz were seen. It was later discovered that weak grid oscillations were also accountable for the 800 MW offshore WPP reaching the de-loading stage [84]. After that, the control software was upgraded by the WPP vendor. On August 24th, 2021, oscillations of 8 Hz in RMS voltage were noted in Scotland. The disturbances occurred twice, each lasting 20–25 s, with around 30 min apart. After re-introducing a few traditional plants to the system, the oscillations were reduced. The oscillation's underlying cause is currently being investigated [41].

It has been observed that SSCCI is an entirely electrical phenomenon and that a large amount of energy is transferred between the converters of WPP and the series compensated network [6]. In addition, a majority of studies have proven that wind farms using DFIGs are susceptible to SSCCI [30, 43, 85]. As a consequence, research community pays significant attention to SSCCI and the accompanying countermeasures. The root cause of SSCCI accidents is the subject of much investigation, and it has been observed in [9] that SSCCI is intimately related to the proportional integral (PI) controller of the current loop of the rotor side converter (RSC). The magnitude and frequency range in which the DFIG shows negative resistance are both influenced by the bandwidth of the current controller loop. Resonant current in the stator of the DFIG produces a similar sub-synchronous current in the rotor when a disturbance occurs. When the sub-synchronous current is detected, the PI controller of the RSC's current loop then modifies the output voltage, which can boost the disturbance and sub-synchronous current, leading to SSCCI. Therefore, by adjusting the PI parameters of the DFIG converter controller, several mitigating techniques have been proposed [86–88].

The proportional gain of the RSC current loop is reduced in [88], which is a damping approach to lessen SSCCI. Although it has limited capability, changing the control parameters may degrade the original control performance. To overcome these challenges, supplementary wide-band damping control strategy for MMC-STATCOM has been proposed to mitigate SSCCI. This method adopts a notch filter to filter only synchronous frequency components to produce the damping control signal, and obtains the corresponding sub-synchronous component to makes MMC-STATCOM exhibit positive resistance even at varying sub-synchronous frequency range [89]. A supplementary damping controller can be applied to a Multi-Terminal DC system and wind turbine converter to effectively secure the integration of WPP and series compensated transmission line [90].

3.3 Sub-synchronous torsional control interaction

SSTCI refers to a problem when a turbo-generator set is connected to power electronic controller, and the mechanical system generates undamped torsional oscillations at sub-synchronous frequencies. The control devices in FACTS and HVDC converter circuits, rapidly change parameters according to the system's power variation in sub-synchronous frequencies [86, 91]. This may cause negative damping, and similar to TI, an undamped oscillation may be produced, which can damage the shaft of a mechanical system. Due to SSTCI, the first accidents happened in 1980 at the Square Butte HVDC and nearby Milton Young turbine plant, while similar events occurred in Ontario and Chester, USA in 1983 and 1987 respectively [56, 87, 92–94]. The latest incident occurred in Hami Wind power system China in 2015, which has a 3000 MW type-4 PMSG based WPP, and power is transmitted through both AC and HVDC transmission lines [95]. Many SSO events were found in 2014, but a severe one was detected on 1 July 2015, in which the torsional oscillation occurred in a conventional turbine generator which is 300 km away from the wind farm. The torsional protective device tripped 3 units of the traditional turbo-generator, resulting in the loss of 1250 MW power generation. The fundamental reason behind the incident was the interaction between the HVDC line and traditional turbo-generator [96]. As per the proposed classification in [36], this incident comes under grid-converter oscillations. However, the oscillations propagated into the transmission line and matched the turbine generator's torsional frequency. Subsequently, the three units were tripped due to the protection scheme, and varying resonance frequencies were detected between 27 and 33 Hz for 3 h and 20 min since the interactions occurred between converter and turbo-generator. Hence, it comes into the SSTCI phenomenon.

Usually, the rectifier sides of HVDC converter control are responsible for the negative damping. The degree of sub-synchronous interaction is influenced by a number of variables, but the management strategy utilized by HVDC to keep power transmitted around a single constant amount is the key reason for the reduced sub-synchronous damping. Constant current or constant power control is a common HVDC rectifier control method for achieving constant power characteristics. Equidistant firing control, which controls the timing of valve firing, is another built-in feature of contemporary HVDC systems that results in reduced sub-synchronous damping. The original HVDC systems' equiangle firing control was intended to be replaced [38], as the equidistant firing control increased the side effect of HVDC on sub-synchronous damping since it essentially eliminated the harmonic generation issue brought on by the previous equiangle firing control [38, 100], though other controllers may also have an effect on it [38]. In particular, the parameters and structure of the rectifier current controller are crucial in determining the level of interaction. A supplementary control circuit may have an impact on the behavior of the control system on the crucial torsional frequencies of a particular unit since the control system, or more specifically, the HVDC control principle, is what causes the interaction [38]. The transfer function of rectifier control is impacted by this supplementary control, also known as sub-synchronous damping control. As a result, the control system related phase shift that causes increasing sub-synchronous oscillation at a certain natural frequency is eliminated. The current research is on Line commutated converter (LCC)-HVDC systems, as LCC-HVDC has rapidly grown in China [101]. An analysis of SSTCI was done for LCC-HVDC and modular multi-level converter (MMC)-HVDC in a power system. It produces higher risk of SSTCI as compared to HVDC systems only [102]. Introducing MMC-STATCOM can reduce the negative damping of existing LCC-HVDC system [103], while the risk of SSTCI may be further reduced by increasing the PLL gain on the rectifier sides of HVDC [104]. The proposed classification and the historical events are summarized in Table 2.

4 SSI analysis techniques

For the analysis of SSI, various methods are used. The most often utilised approaches, i.e., frequency scanning technique, complex torque coefficients analysis, eigenvalue analysis, impedance-based model analysis, and transient simulation analysis, are reviewed in this section. According to existing literature, Table 3 summarises the main features and constraints of the different techniques.

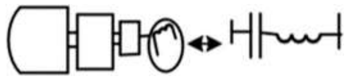
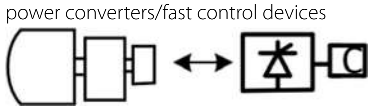
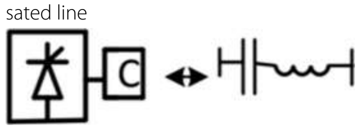
4.1 Frequency scanning technique

Linear analysis is a technique used in frequency scanning. This method, which is based on a positive sequence network topology, can be used using an equivalent circuit. For instance, it is possible to determine the transient equivalent impedance of the entire system Z(s) as a function of frequency when seen from a single point inside the system. The curves of equivalent resistance R(s) and reactance X(s) under different frequencies can be used to evaluate the stability by looking for the presence of a sub-synchronous frequency where the reactance is zero while the resistance is negative. PSCAD/EMTDC/MATLAB can be used to implement frequency scanning [105]. Frequency scanning is an easy and uncomplicated technique. Before conducting a more in-depth examination, it can be used to screen for SSI risk. However, the system analysis of network with several power electronic devices is severely constrained by this method. Additionally, it is inappropriate when taking into account how wind turbines behave dynamically in the event of failures [106].

4.2 Complex torque coefficients

Reference [107] suggested to perform a study of complex torque coefficients. By computing the shafting mechanical damping coefficient D_M and electrical damping coefficient D_E, this method assesses the likelihood of a system to experience SSO. The generator rotor experiences a

Table 2 Comparison analysis of proposed classifications and historical events due to SSI

Type of proposed SSI phenomenon	Triggering Factor	Characteristics	Practical Incidents		
			Location	Year	Severity
SSR	Realistic level of series compensation in a transmission line	Weak damping caused by negative rotor apparent resistance Interaction between shaft system and series capacitor 	Mohave, California, USA [15, 61]	1970	Failure
			Navajo, USA [31]	1976	Test
			Cholla, USA [97]	1978	Test
			Shangdu, China [34, 75, 98]	2011	Test
SSTCI	Rectifier side of the HVDC system Inappropriate parameter tuning of power conveters	Fast control action of devices causes variable torsional frequency Interaction between shaft system and power converters/fast control devices 	Square Butte, USA [92, 93]	1980	Test
			Ontario, USA [56]	1983	Test
			Chester, USA [87, 94]	1987	Test
			Hami, Xingjiang, China [22, 88, 99]	2015	Failure
SSCCI	Level of series compensation Weak AC system without involving of series compensation Power electronics devices with inappropriate parameter tuning	Wide-ranging transformation between a system with several sources and multiple terminals Variable resonance frequency Adverse impacts on the other existing stable modes in the system Interaction between power converters/fast control devices and a series compensated line 	Minnesota, US [29, 45]	2007	Failure
			ERCOT, Texas, USA [19, 77–80]	2009	Failure
			Guyuan, Hebei, China [27, 81]	2012	Failure
			ERCOT, Texas, USA [83]	2017	Test
			Hornsea U.K [84]	2019	Failure
			Scottish wind farm [41]	2021	Test

small disturbance that is imposed on a regular basis, and the electromagnetic torque increment ratio ΔT_E to $\Delta\delta$ can thus be represented as:

$$\frac{\Delta T_E}{\Delta\delta} = K(\mathcal{F}) + j\mathcal{F}D(\mathcal{F}) \tag{5}$$

$K(\mathcal{F})$ and $D(\mathcal{F})$ coefficients comparison and analysis can be used to determine the system stability at the current frequency. The complex torque coefficients method have drawbacks, including inability to accurately and totally predict the system behaviour in the relevant frequency range. However, it has been asserted that the approach of torque coefficients can be used with many machines as long as generator shaft dynamics and speed variations are taken into consideration. Using the complicated torque coefficients method, mechanical and electrical damping at various frequencies may be quickly visualized. It can be implemented using time-domain simulation tools or linearized mathematical models [108]. However, the complex torque coefficients method is more likely to be used as a traditional SSO analysis tool [109].

4.3 Eigenvalue analysis

For analysing small-signal stability, eigenvalue analysis is widely used. It is necessary to first establish the mathematical models (state equation and algebraic equation) for the various system components. After that, the algebraic variables can be eliminated during linearization. The system state space matrix can finally be expressed as [74]:

$$\Delta\dot{X} = A\Delta X \tag{6}$$

The eigenvalue of matrix A can be easily determined. The conjugate roots each refers to a different oscillation mode. While the imaginary portion of the eigenvalue denotes the corresponding oscillating frequency, the real portion of the eigenvalue can be understood as damping, which primarily impacts system stability. Eigenvalue analysis has been frequently utilised to determine how other factors, such as wind speed, operating state, series compensation level, and controller settings, affect the SSI modes because of its precision and accuracy [110]. A great deal of useful information may be obtained through eigenvalue analysis, and the findings are beneficial for suppression strategies [101–104]. The risk of "dimension disaster" makes it challenging to derive the system state equation when eigenvalue analysis is used on a high-order system. Additionally, this method can only produce electrical damping on a number of related isolated frequency points,

Table 3 Comparison of SSI analysis methods

Analysis Techniques	Advantage	Limitations	Applications
Frequency scanning techniques	Simple and easy to implement by utilizing equivalent circuits or simulation tools Computational attractive Cost-effective	Approximate method For accuracy, the results must be verified using time domain simulation It is not possible to consider the dynamic properties of systems during faults	To identify steady-state SSR, SSTCI and SSCCI To determine the system operating circumstances that influence SSI
Eigenvalue analysis	Accurate analysis and provides a clear insight into Subsynchronous interactions Reveals details about the damping and frequency of every system mode Finding the involvement of state variables and component sensitivity is simple	Restricted to very large systems Nonlinearities cannot be included Device switching characteristics are ignored Expensive method Require detailed system representation Fails to identify transient SSR	Helpful for creating SSI countermeasure controllers To determine the system's operational circumstances that affect SSI
Complex torque coefficients	Displaying the mechanical and electrical damping coefficient trends over a wide range of frequencies	Mostly applied to the mechanical oscillation	To identify SSTCI and torsional interaction of SSR
Impedance-based model analysis	Finding the oscillation path and component sensitivity is possible due to the impedance-network model, which preserves the network topology	Improved modeling methods and suitable stability criteria are required Challenging frequency domain modeling techniques	Used for SSCCI analysis
Transient simulation analysis techniques	Allows for precise SSI investigations under varied disturbances	For self-excitation study, not recommended Needs a thorough system representation Not helpful for determining the internal relationships among different variables	Verify the outcomes of the eigenvalue and frequency scanning techniques

not a curve of system damping across the appropriate frequency range. Therefore, eigenvalue analysis is not useful for characterizing properties in the general frequency domain [111].

4.4 Impedance-based model analysis

The impedance models created in a stationary frame (phase domain) and a synchronous frame (d-q domain) are the two primary categories in which impedance-based analysis approaches in the frequency domain can be classified [44]. During the modeling, the target system is typically split into two subsystems of source and load. The information in the source subsystem mostly relates to various generator-side objects, such as converters, wind farms, and turbine generators. Different loads or transmission lines are frequently present in the load subsystem [112]. After that, by observing the source-load impedance ratio, the system stability can be determined using an upgraded or generalized Nyquist Stability Criterion (GNC) [43]. This method has been extensively utilized to look into different system stability challenges, such as SSI in wind farms. The approach has the benefit of accounting for different converters and conventional generators. Future applications of the impedance-based model analysis are very feasible due to the increasing uses of power electronics devices in power systems but it needs better modeling techniques [113].

4.5 Transient simulation analysis

Transient simulation analysis can be used to show the trends of time-domain variables. Depending on the time scale, simulation can be divided into electromagnetic transient, electro-mechanical transient, or dynamic mechanical simulation. The results of theoretical study in relation to the modelling of SSI have been validated by electromagnetic transient simulation analysis. It can be used in conjunction with other techniques, such as frequency scanning and eigenvalue analysis [44], to shorten the time needed to investigate the problem. In contrast, electromagnetic transient simulation is thought to be more suitable for SSI in wind farms than electro-mechanical transient simulation [114]. Simulator accuracy and speed are big challenges as converter control techniques are being used more and more in power systems [43]. A current issue is how to implement the electromagnetic transient simulation of big systems. The trends of each variable may be seen on the screen thanks to the time-domain simulation technique. However, this does not allow for the finding of the intrinsic correlations between system variables for oscillation mechanism analysis and suppression measure construction.

5 Solution techniques and their challenges

This section discusses the SSI mitigation techniques and their challenges according to the existing literature that deals with the proposed classification of the emerging SSI phenomenon. The features and limitations, along with whether they are applicable for the network sides or generation sides, are summarized in Table 4.

5.1 Mitigation techniques for SSR

5.1.1 Reduce the degree of series compensation

Higher compensation level causes higher risk of SSR, and thus it requires to reduce the series compensation at the planning stage. However, an incident occurred in Guyan, China, due to SSCCI with the compensated line approx. 6.67% [29, 115].

5.1.2 Improve grid strength

Generally, power plants are located far away from the grid or local load. The required long transmission lines increase the net reactance thus, reduce the short circuit ratio, resulting in weaker grid [116, 117]. As a result, the steady state based SSR phenomenon can arise. This can be mitigated by improving the AC system strength by introducing, e.g., a voltage source converter, HVDC line etc., though it may cause risk of SSCCI [118, 119]. This is revealed when an SSCCI incident occurred in Hami PMSG based WPP connected with a weak AC grid system [98].

5.1.3 Bypassing series capacitor

This technique is inexpensive and feasible for practical systems by developing an intuitive oscillation sensing algorithm. If the calculated magnitude of synchronous current exceeds a specific set value. In that case, the algorithm provides command and bypasses the series capacitors at particular instant. In contrast, a reinsertion algorithm is applied to reinsert the series capacitors when the voltage level is under the threshold value [32]. However, SSI can happen in a system without series compensation as stated hereinbefore.

5.1.4 Damping control by FACTS devices

FACTS devices are effective solutions for mitigating SSI and achieving their primary objective of the controller [120, 121]. Several studies have been done to utilize the FACTS devices, for example, SVC, STATCOM, TCSC, GCSC, UPFC, and SSSC, for mitigation of SSR by manipulating internal control to damp out SSR frequency via reshaping network impedance without affecting their primary objective, i.e., voltage control, power flow control, reactive power compensation,

Table 4 Summarization of solutions techniques and challenges for SSI mitigation

Proposed classification	Mitigation techniques	Advantages	Challenges	Applicable for	
				Generation side	Network side
SSR	Reduce the degree of series compensation [22, 79]	Not required any expensive damping methods	Only appropriate for the designing stage The risk of SSCCI may rise		✓
SSR	Improve grid strength [80, 89, 98]	Not required expensive damping methods	Only appropriate for the designing stage The risk of SSCCI may rise		✓
SSCCI	Installing heterogeneous wind power plant [16, 81, 82]	Wind plant more stable Invulnerable to SSCCI	Complications in modeling and studies cannot be accumulated to signify the entire wind farm Risk of SSCCI	✓	
SSR	Bypassing series capacitor [30]	Inexpensive efficiently executed to practical system	It can itself cause the sub-synchronous phenomenon Loss of power		✓
SSCCI	(on/off) switching of WPP [18, 74]	Total protection	Require advance equipment for detection Loss of power	✓	
SSR	Damping control by FACTS devices[55, 56, 84–86]	Flexible and robust for a wide range of operation Effectively mitigate SSI	Expensive VSC based FACTS devices can also trigger SSCCI event		✓
SSTCI	Damping controls via HVDC [89–91]	Easily added SSDC to HVDC	VSC based HVDC can trigger SSCCI event		✓
SSTCI	Industrial sub-harmonic relay	Detect the time varying oscillations	Source of Error Expensive		✓
SSR	Shunt-VSC[75, 92]	Inexpensive efficiently executed to practical system	Only devoted for SSI damping, not for other tasks		✓
SSCCI	Regulating control parameters of WTC[79, 83, 94, 95]	Not required any expensive equipment	The control parameters of the WTC are not easily accessible Various manufacturers may have different WTC controls Individually adjusting each WG of a wind farm is impractical and uneconomical		✓
SSCCI	Virtual synchronous generator control[94, 95]	Stabilize Sub-synchronous oscillation along with providing inertia	Expensive Technology is not mature	✓	
SSR	PV Solar based damping [75, 96, 97]	Controllability of both active and reactive power	Expensive An SSCI event can be participated by VSC-based converters		✓
SSCCI	SDC with GSC [20, 22, 82, 98–105]	Assemble in converter controller Inexpensive solution Reactive power control capability can beutilized for damping Effective SSI mitigation	Low rated Control capability is less for damping SSI It required greater damping control At low wind speed and a high degree of compensation, voltage control capability would be restricted Require cautious tuning parameter	✓	

Table 4 (continued)

Proposed classification	Mitigation techniques	Advantages	Challenges	Applicable for	
				Generation side	Network side
SSCCI	SDC with RSC [104–115]	Assemble in converter controller High rating as compared to GSC controller; Control capability is more than the GSC Active and reactive power are directly control Effective mitigation at high compensation It required lesser effort for damping control The controllability index is high for rotor voltage control during SSI RSC controller directly affects the rotor resistances	It might be destabilized in another mode Require extra work and care for tuning It can destabilize the Sub-synchronous mode due to the high gain of the RSC controller Due to increased current control, gain reduces aggregate equivalent resistance It deteriorates the control bandwidth of DFIG and does not meet the FRT requirement	✓	
SSCCI	SDC at both RSC and GSC [104, 116]	Improve FRT capability along with other parameters Increases control capability	Complex approaches Saturation of converter	✓	

stability, power quality, conditioning, etc. [122–124]. They are flexible and robust for a wide range of operations and effective SSR mitigation [125] 126. The only challenge with this technique is its high cost, although it could be economical when the FACTS controller has already been built into the system [127]. In addition, a VSC-based FACTS controller may also lead to SSCCI event [86, 91].

5.1.5 Shunt-VSC

Due to the fundamental operating frequency, cost, rating, and equipment size increase, using FACTS devices to mitigate SSI may not be economically feasible. However, the cost of FACTS devices could be reduced by designing a special-purpose shunt-VSC to generate a compensated signal at the extracted sub-synchronous frequency instead of the fundamental frequency. The sub-synchronous component is extracted by a notch filter and a bandpass filter [128, 129].

The challenge in this technique is the accurate extraction of the sub-synchronous frequency because of varying sub-synchronous and fundamental frequencies with time during SSI events. Thus, it is challenging to track the exact frequency while it's devoted only to SSI damping without performing other tasks [130].

5.1.6 PV Solar based damping

Although FACTS devices can alleviate the SSR issue proficiently, they can't exchange active power with the network and are also costly. Reference [131] utilized a PV solar farm as STATCOM, namely PV-STATCOM, to mitigate SSR in a steam turbine-driven system with SC transmission lines. The PV solar farm can work as a STATCOM with its whole inverter limit for SSR alleviation from evening to nighttime. If a system deficiency/fault triggers SSR during the daytime. In that case, the PV solar stops its normal active power generation and its whole inverter ability works as PV-STATCOM for SSR counteraction. When the SSR is damped, the PV solar farm returns back to its ordinary real power generation. However, VSC-based PV-STATCOM raises the risk of SSCCI [132, 133].

5.2 Mitigation techniques for SSTCI

5.2.1 Damping controls via HVDC

Bulk power can be transferred using an HVDC transmission system from a remote location to grid utility efficiently and effectively. A converter controller is used at sending end and receiving end [134]. A proportional resonate controller is applied at sending end of modular multi-level converter HVDC link to suppress SSTCI [135], and some further supplementary damping controllers can be used to existing HVDC converters. However, a VSC-based HVDC converter may destabilase other stable mode of the existing system.

5.2.2 Industrial sub-harmonic relay

Industrial sub-harmonic relay is used to detect SSTCI, and for the damping of SSTCI an active damping controller can be used. The microprocessor based sub-harmonic protection are used to estimate SSTI, but there are a number of sources of errors, so analog sensors are required to sense and overcome the errors. However, the overall mitigation techniques are very expensive [136].

As per authors best knowledge very few literature exists to deal with mitigation of SSTCI, while the current research is mainly on analysis of SSTCI [102, 137, 138].

5.3 Mitigation techniques for SSCCI

5.3.1 Regulating control parameters of WTC

The DFIG-based wind turbine control (WTC) structure is shown in Fig. 5. The control parameter of the controller affects the damping of the system. For instance, the output voltages from the Rotor Side Converter (RSC) and Grid Side Converter (GSC) are controlled by the PI current controllers. PI controller parameters have an impact on the damping of SSCCI, which has been proven by Eigenvalue analysis [79, 83, 94]. The torque loop gain and reactive power control reduce the SSCCI damping. Thereupon SSI mitigation technique was developed by detecting a sub-synchronous component in real-time, and consequently, the gain of the current controller of the RSC is reduced. Besides, SSCCI damping can also be improved by enhancing the rise time of the RSC controller. Thus, optimal PI controller parameters improve the damping ratio, but the challenge is that if the value crosses the defined range, the DFIG system may be disturbed due to fault sensing [95].

5.3.2 Installing heterogeneous wind power plant

Deploying a different type of wind farm instead of the same type of wind farm is less prone to SSCCI [25], for example, adding Type-4 (PMSG with full scale converter) wind turbines, which are able to provide positive damping to Type-3 (DFIG with partial scale converter) wind turbines [139, 140]. This can be adopted to mitigate the effect of SSCCI in the WPP [141]. However, it is difficult to model and study the wind farm as it cannot be accumulated to signify the entire wind farm.

5.3.3 (On/off) switching of WPP

In this strategy, selecting a suitable number of WPP and turning off the entire WPP by providing a tripping signal helps stabilize the unstable mode of SSCCI [22]. This is accomplished by determining the equivalent impedance [27]. This arrangement is suitable for the global protection of power systems from SSCCI. However, separate communication is required for the command and coordination unit, and the major drawback is the cost of power loss.

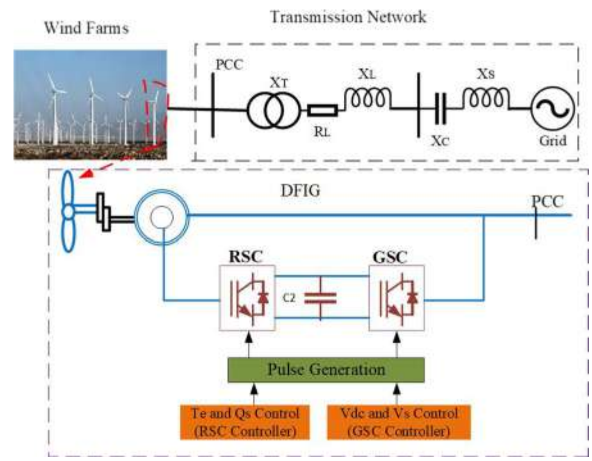


Fig. 5 DFIG-based WTC control structure

5.3.4 Virtual synchronous generator control

This technique recently has been developed to mitigate SSCCI by providing virtual inertia [142]. It can simulate the dynamic stability characteristics of a wind farm by providing virtual inertia via controlling the back-to-back converter of the wind turbines [143, 144]. Most of the current research is on the design of an SDC to reshape the system's overall impedances. There is not much literature on virtual synchronous generator control found on the impact of SSO caused by SSCCI, while this technology is not mature and is an expensive solution.

5.3.5 SDC with GSC

GSC's control loop provides the advantage of adding a damping controller. The structure of GSC with DC-link has a damped characteristic with capability similar to STATCOM but having additional advantages of reduced cost [145, 146]. Supplementary damping can be added to the q-axis of the stator voltage control loop, as shown in Fig. 6 to damp SSCCI by modulating the reference signal. The ideas have been utilized in numerous investigations [31, 147, 148]. A multi-channel damping controller scheme was proposed in which each channel consists of modal speed as an input signal and includes the oscillation associated and damped by using phase and gain compensators as shown in Fig. 7 [149].

A PSO-based technique has been used to optimize the Lead-Lag Compensator (LLC), as shown in Fig. 8 (a), with its limitations being only operable at a specific operating point, whereas WPP is non-linear and is operable in a wide range. Therefore, an adaptive Fuzzy logic-based damping controller (FLDC) was introduced, as shown in Fig. 8b, and a comparison was also done between FLDC

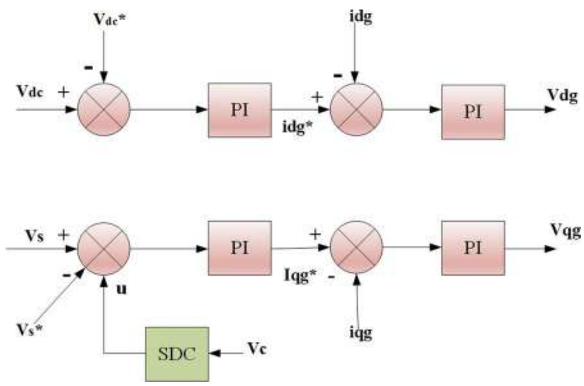


Fig. 6 With an auxiliary SSR damping at q-axis loop

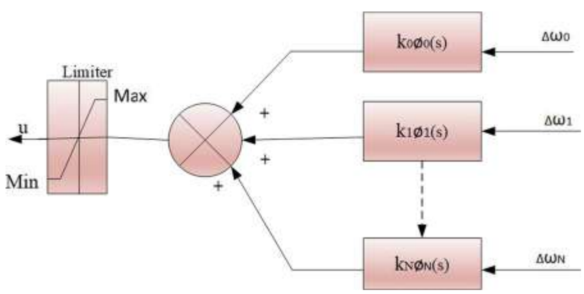


Fig. 7 GSC SDC with multichannel gain and phase shifters

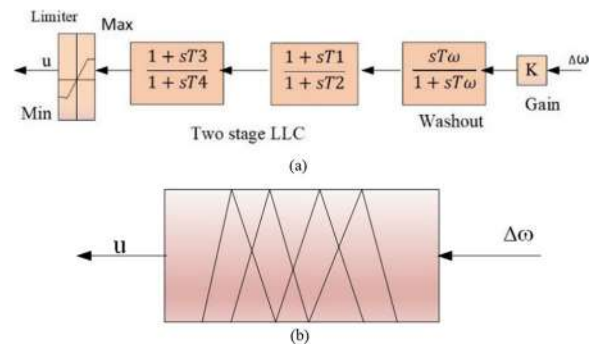


Fig. 8 **a** PSO optimized with lead-lag networks, **b** fuzzy controller

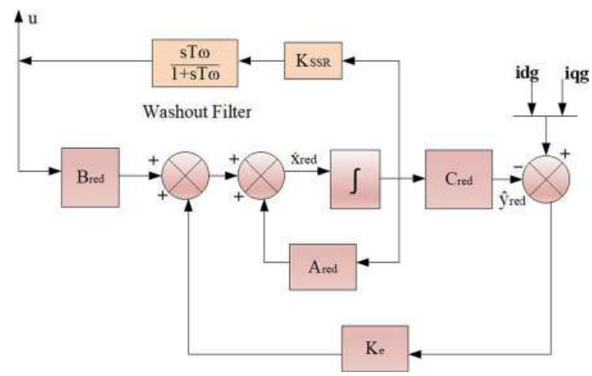


Fig. 9 State-feedback controller, LQR as state observer

and PSO-based conventional damping controller, thus highlighting the better performance of FLDC [31].

Further shortcoming of the above techniques includes the use of speed deviation as an Input Control Signal (ICS), which is not an optimal choice for damping controller. So for the effectiveness of SDC, a voltage across the series capacitor is used as an ICS [18]. However, the voltage across the capacitor isn't locally accessible at the WPP and must be transmitted via a separate communication channel, which may cause control delays.

Subsequently, an SDC with a feedback controller is proposed which utilizes an optimal quadratic method to adjust the terminal voltage reference of GSC in [150]. The stator current (d-q segment) is used as an input to the controller, and the performance is analyzed and found to be satisfactory. The state feedback controller, which has a gain and a high-pass filter (HPF) for blocking, is used to derive the law. As shown in Fig. 9, the controller output is applied to the GSC's stator voltage control loop.

The observed state-feedback controller is mathematically complex because it involves model order reduction and state estimation, making it challenging to implement in the existing wind farms. Therefore, for wide operation, a feedback linearized sliding mode controller (FLSMC) is designed, which is a robust non-linear feedback controller for a wide range of operations, and its output is applied to the stator control loop of GSC [151].

Recently, a probabilistic DFIG-based PSS was designed based on LLC, which adds its output into the q-axis of the inner controller and utilizes capacitor voltage as ICS [139]. In [152], PI-based current controller was replaced by partial feedback linearization (PFL), as shown in Fig. 10. Because of the appropriate switching pattern, it can mitigate SSI at operating conditions at a wide range, while transforming the non-linear model into low order partially linearized model [114]. However, mathematical burden limit needs be reduced.

5.3.6 SDC with RSC

RSC's effectiveness over GSC is more dominant with auxiliary damping controller as it has superior performance for a higher degree of series compensation, high controllability index, while its controller can directly affect the rotor resistances [153].

A supplementary damping controller was added at the inner control loop of RSC. The controller is based on multi-input multi-output state-space methodology with the locally available rotor and stator currents as the input control signals [154, 155], as shown in Fig. 11. The

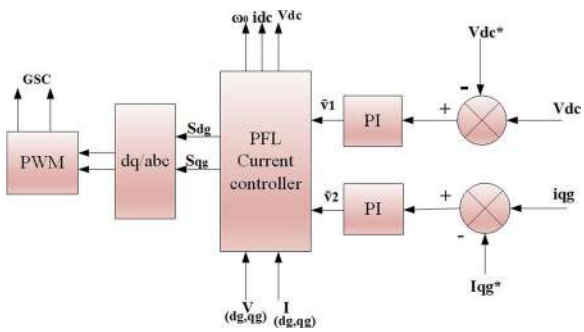


Fig. 10 PFL based current controller

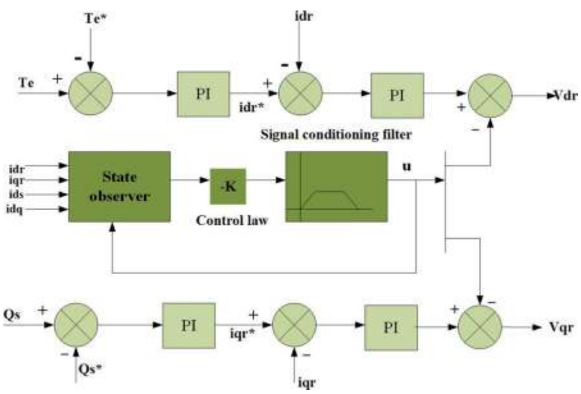


Fig. 11 The supplementary SSI damping Observer-based state-feedback controller

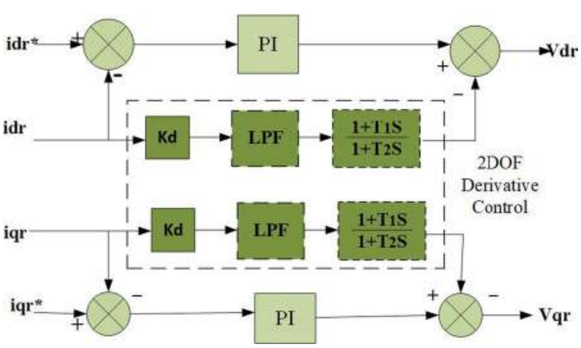


Fig. 12 2DOF added current control loop of RSC

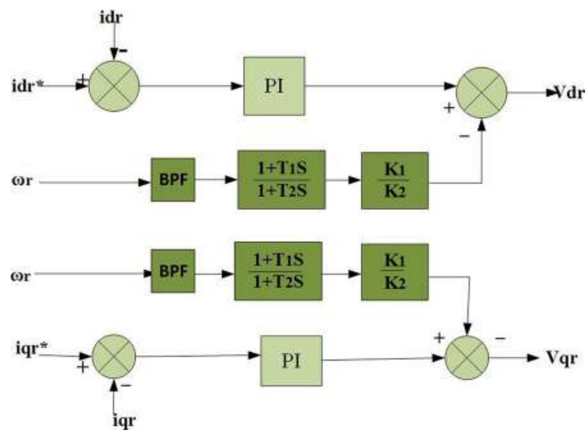


Fig. 13 Feedback filtering (LLC and BPF)

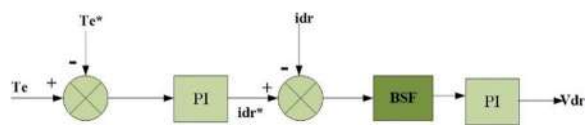


Fig. 14 Feedforward filtering (BSF)

challenge with this controller is that its performance may deteriorate considering the desired transient response of the DFIGs. To rectify this problem, a linear matrix inequality (LMI) method has recently been proposed. A two-degree of freedom (2DOF) derivative control strategy was developed as shown in Fig. 12, and implemented at the d-q axis of the output voltage of the inner control loop of RSC [156]. This technique improves overall system stability against SSCCI along with fault ride-through capability (FRT) of DFIG. The method was further improved by introducing LLC and low pass filter (LPF) to eliminate all possible high-frequency noise [157]. References [114, 152] have developed a PFL non-linear feedback controller to replace the RSC inner current controller. In [158], an H-infinity-based robust non-linear current controller was designed and replaced with the existing PI-based current controller, and proved that it could damp SSCCI at all possible degree levels of series compensation and wind speed.

Another study using a filter to suppress SSCCI was added to the RSC control loop [159]. There are two methods to add a filter in RSC. One method is to only allow sub-synchronous components through the bandpass filter of an input control signal, and based on the filter output, ICS then generates a compensated signal. In [159], a combination of LLC and BPF was utilized, and the gain ratio, as shown in Fig. 13, was optimized through PSO. The proposed feedback filtering used speed deviation as an input control signal, and output was added to the control loop output of both d-q axis of RSC in [160]. The challenge with this filter technique is that it is not feasible for a time-varying wide range of practical systems. The second way to stop over the sub-synchronous component is to use a notch filter, which is added at dq axis control loop of RSC. A feedforward filtering approach is used to filter out sub-synchronous frequencies. A detailed investigation and placement of notch filters were done in [161], and the controller design is shown in Fig. 14. These filtering techniques are easy to implement and economical, but with the limitation of tunings at a particular sub-synchronous frequency.

Implementing an SDC on the RSC side's active power control loop which utilizes a turbine generator speed as an ICS, has also been proposed. In a practical installed power system of Argentinian, a transmission line with series compensation was used in the wind power system and conventional power system along with load distribution to suppress SSCCI. SDC was added at the RSC d-axis of rotor voltage on the active power control loop, and active power of the wind farm was used as an output for ICS to the SDC [162].

5.3.7 SDC at both RSC and GSC

Implementing a supplementary damping controller at RSC and GSC increases the control capability index and improves stability performance. In [163], the exiting PI controller was replaced with the Exact Feedback Linearization (EFL) controller in GSC and RSC. EFL controller alters the non-linear dynamic system into a linear system. More information can be referred in [145, 146]. This proposed technique provides stability throughout the wide range of sub-synchronous frequency, though PI-based controllers have no guaranteed stability. A State-Feedback Linearization (SFL) controller was then designed that uses EFL to replace the existing PI-based current controller in both RSC and GSC [152]. The challenges with these techniques are complex implementation and converter saturation issues.

Table 5 reviews the mitigation strategies that can be used to address past SSI-related incidents. This summary table makes it simple to handle future incidents. Bypassing series capacitor is the best mitigation strategy for real power systems to handle SSR events, as in comparison to other SSR mitigation strategies, it is less expensive as fixed series compensation is the primary source of SSR. Although it is also cost-effective to minimize the degree of series compensation, an SSR event occurred in China in 2015, where the level of compensation was relatively low. Thus, it is inadequate to simply rely on the series compensation reduction techniques. There are very few mitigating approaches available for the reduction of SSTCI. As the HVDC controller device is also responsible for this interaction, providing a supplemental damping controller to the HVDC is the optimum mitigating method for SSTCI. This method has a high-speed response, is dependable, and is more affordable than other methods.

SDC with GSC is one of the optimum mitigating strategies for SSCCI, which typically occurs in WPPs, according to historical event witnesses. SDC with GSC mitigation strategies is inexpensive, reliable, and simpler than other systems, and it may be readily deployed in an existing power system. Regulating the WTC's control parameters is another effective mitigation strategy, although this is required at the planning stage and would not work with existing systems. GSC using RSC techniques may cause instability in other stable modes and degrade DFIG's control bandwidth, which may cause it not to meet grid code requirements. Another method, as per the existing literature, is to turn on/off the WPP. However, it is not a permanent solution, as significant power loss could occur.

6 Future trends, challenges and recommendations

The future trends are oriented toward renewable energy resources, leading to the involvement of power electronics devices in the generation and utilization. In recent years several power failures have occurred in US and China due to SSI in renewable power generation systems. Consequently, the emerging SSI issues in grid-connected wind farms have gained high attention among the current research community. Accordingly, this paper reviews a wide range of SSI phenomena and associated mitigation strategies. Despite this, developing an efficient and practical SSI mitigation control system still presents several difficulties as follows.

(i) Due to commercial privacy issues, most turbo-generator set models are either inaccessible or immature, because there is a lack of standardization and validation. Therefore, sub-synchronous studies cannot be carried out at the planning stage by transmission system operators or power system engineers.

(ii) To analyze the system, aggregated model is considered for simplicity, in which hundreds of wind generators are supposed to be the same type and interconnected to a single bus in the WPP. But in a practical system, there may be several wind farms with various locations, each of which may include a variety of wind generators and WTC controllers. As a result, the practical SSI mitigation performance may differ from the best performance outcomes found in the simplified simulation model.

(iii) Most of the SSI damping control strategies suggested in the literature are of academic interest, and the main focus has been placed on creating a viable control strategy. A method that can be quickly and readily executed on a workable system is urgently needed.

(iv) As already been established, during an SSI occurrence, the oscillation frequency is not constant but changes over time. Estimating the instantaneous frequencies for oscillations with time-varying frequencies is essential for practical mitigation strategies. But it is a challenging task to track the com-

Table 5 Summarization of solutions techniques for practical SSI events

Sub-synchronous resonance incidents

Mitigation solution	Mohave, California, USA (1970)	Navajo, USA (1976)	Cholla, USA (1978)	Shangdu, China (2011)
Reduce the degree of series compensation	✓ © ® $	✓ © ® $	✓ © ® $	✓ © $
Improve grid strength	✓ © $	✓ © $	✓ © $	✓ © $
Bypassing series capacitor	✓ ® © $	✓ ® © $	✓ ® ©$	✓ ® © $
Damping control by FACTS devices	✓ ® * $	✓ ® * $	✓ ® * $	✓ ® * $
Shunt-VSC	✓ ® ©$	✓ ® ©$	✓ ® ©$	✓ ® ©$
PV Solar based damping	x	x	x	✓ *

Sub-Synchronous Control Torsional Interaction incidents

Mitigation Solution	Square Butte, USA(1980)	Ontario, USA(1983)	Chester, USA(1987)	Hami, Xingjiang, China (2015)
Damping controls via HVDC	✓ © $ ®	✓ © ® $	✓ © ® $	✓ © ® $
Industrial Sub-harmonic Relay	✓ * ®	✓ ® *	✓ ® *	??

Sub-Synchronous Converter Control Interaction incidents

Mitigation Solution	Minnesota, USA (2007)	ERCOT, Texas, USA (2009)	ERCOT, Texas, USA (2011)	Guyuan, Hebei, China (2012)	Guyuan, Hebei, China (2016)	ERCOT, Texas, USA (2017)	Hornsea UK (2019)	Scottish wind farm (2021)
Installing a heterogeneous wind power plant	✓ * $ ©	✓ * $ ©	✓ * $ ©	✓ * $ ©	✓ * $ ©	✓ * $ ©	✓ * $ ©	✓ * $ ©
(on/off) switching of WPP	✓ © ® $	✓ © ® $	✓ © ® $	✓ © ® $	✓ © ® $	✓ ©® $	✓ © ® $	✓ ©® $
Regulating control parameters of WTC	✓ © $	✓ © $	✓ © $	✓ © $	✓ © $	✓ © $	✓ © $	✓ © $
Virtual synchronous generator control	✓ $	✓ $	??	✓ $	✓ $	✓ $	??	??
SDC with GSC	✓ © ® $	✓ © ® $	✓ © ® $	✓ © ® $	✓ © ® $	✓ © ® $	✓ © ® $	✓ © ® $
SDC with RSC	✓ © $	✓ © $	x	✓ © $	✓ © $	✓ © $	x	✓ © $
SDC at both RSC and GSC	✓ * $	✓ * $	x	✓ * $	✓ * $	✓ * $	x	✓ * $

✓-Applicable, x-Not applicable, ©-Cost effective, ®-Reliability

*-Complex, ??-under research investigation, $-Good speed Response

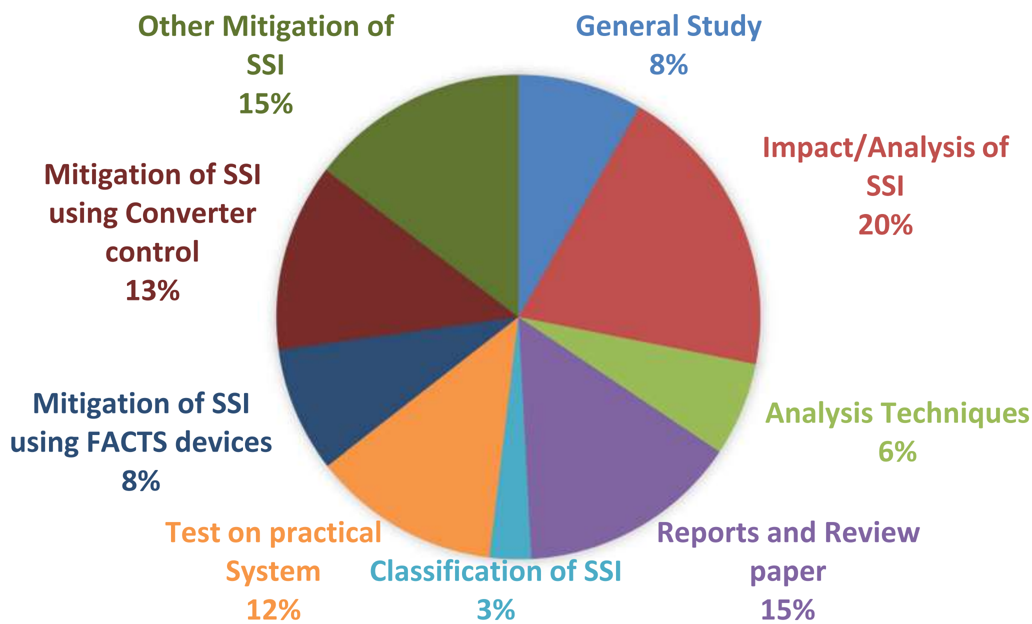


Fig. 15 Percentage of articles in WPP on SSI for each research category

bined synchronous and other sub-synchronous and super-synchronous frequency components. A few publications on the dynamic tracking of sub-synchronous and super-synchronous frequency components have been published. As a result, it is desirable to take the oscillatory issues brought on by SSI into account while constructing the system on the generating and transmission sides. It should be the manufacturer's responsibility to enhance its WTC control design, to include acceptable SDC schemes like feedforward or feedback filter-based mitigation methods. A straightforward and useful strategy should be incorporated into the design of SDC to be effective for oscillation frequency variations.

The overview of SSI related research publications from 1937 to 2022, and SSI in WPP from 2006 to 2022, is further discussed here. It shows that the number of published publications on SSI in WPP has steadily increased after 2009 due to the actual SSI event at the Zorillo-Gulf wind farms. These publications can be divided into five research categories for additional analysis because they instantly highlight the primary focal areas of SSI in WPP research during the last decade. The percentage of papers for each study category is depicted in Fig. 15. The chart reveals that WPP has covered more research articles on the analysis and impact of SSI. Twelve percent (12%) of the research article have been published on testing of SSI in practical power systems. However, in the SSI mitigation category, the researchers primarily focused on SSI mitigation utilizing FACTS, followed by using converter control. Also, many papers on various mitigation measures and SSI analytic approaches on WPP have been published, but very few papers were on the classification of SSI and its terminology. Most papers have been published on analysis and impact of SSI from 1937 to 2022, while the research is still ongoing. This area of the research field has become more comprehensive due to the involvement of power electronic devices and the integration of renewable energy in electric power systems.

7 Conclusion and future scope

A proposed classification has been discussed in this paper which addresses many solutions and their challenges, including active damping controllers, control scheme parameters, degree of series compensation, etc., used in WTCs and other mitigation techniques. The conclusions are summarized below.

- The emerging SSI in renewable energy integrated power systems, focusing on wind- integrated power systems, has been highlighted and explained in this paper. These oscillations have not been clarified in the IEEE standard but tend to follow the literature's findings. As a result, this paper has proposed a new classification scheme for SSI based on oscillation's dominant source. The new classification makes it easier to grasp the evolving SSI in real-world power systems with high penetration of renewables. SSI is divided into torsional, Sub-Synchronous Resonance, Sub-Synchronous Converter Control Interaction, and Sub-Synchronous Torsional Control Interaction in this manner.

- Several existing strategies and analyses with their challenges have been reviewed in this paper. As the high degree of wind integration can cause instability, the damping system used on the generation side must be more effective than any other units. Among many techniques, SDC applied to GSC is the most effective strategy for reducing SSR as per the literature review, while the cost of using these devices to mitigate SSR is minimal. It should be noted that SDC with RSC performs well at high levels of series compensation and meets grid code requirements.
- The design of supplementary damping control should be prioritized in the future. Modification of WTC control and special purpose VSC control based SDC are included. SDC should be built with a simple interface and realistic approach that can be used for dampen the system oscillation at a wide range of frequencies. Furthermore, simultaneously monitoring fundamental and sub-synchronous frequency components are challenging for developing a realistic and successful SSI mitigation strategy.

Abbreviations

SSI	Sub-synchronous (SS) interactions
WTGs	Wind turbine generators
WTC	Wind turbine converter
DFIG	Doubly fed induction generator
HVDC	High voltage DC
FACTS	Flexible AC transmission system
SC	Series compensated
PSSs	Power system stabilizers
SSR	sub-synchronous resonance
WPP	Wind power plant
SDC	Supplementary damping control
IGE	Induction generator effect
TI	Torsional interaction
TA	Torque amplification
DDSSO	Device-dependent SS oscillations
SSCCI	SS converter control interactions
SSTCI	SS torsional control interactions
VSC	Voltage source converter
RSC	Rotor side converter
GSC	Grid side converter
LLC	Lead-lag compensator
ICS	Input control signal
PMSG	Permanent magnet synchronous generator
WTC	Wind turbine converter

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