IEC TR 63401-2

Edition 1.0 2022-06

TECHNICAL REPORT

colour inside

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

IEC TR 63401-2:2022-06(en)

IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.160, 27.180, 29.020

ISBN 978-2-8322-3929-2

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

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FOREWORD

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IEC TR 63401-2 has been prepared by subcommittee SC 8A: Grid Integration of renewable energy generation, of IEC technical committee TC 8: Systems aspects of electrical energy supply. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
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.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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- withdrawn,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 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.

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.

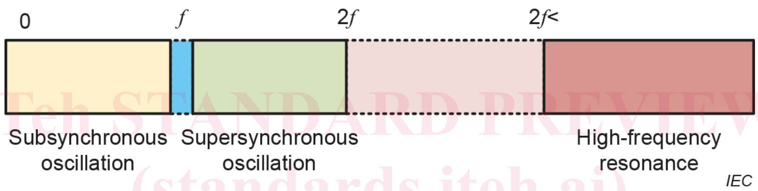

Figure 1 – Multi-frequency oscillations in the modern power system with high-share of renewables and power electronic converters

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:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

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].

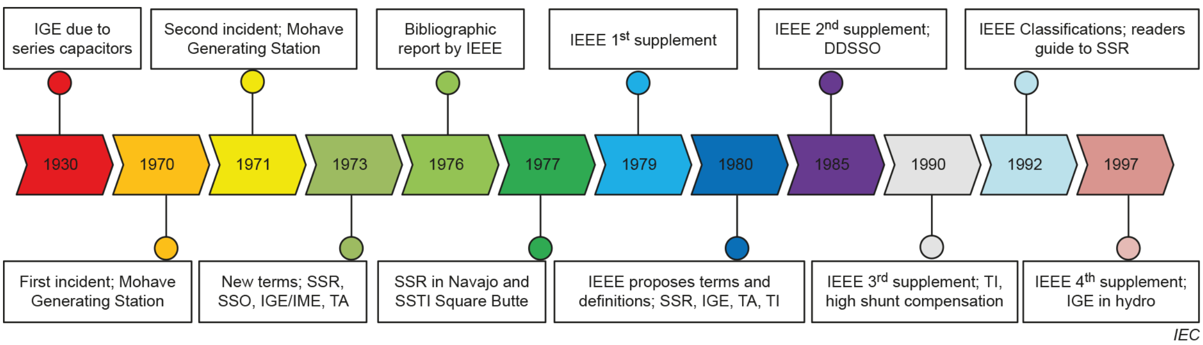

Figure 2 – Timeline of the historical developments of SSO terms, definitions and classification [12]

1 Numbers in square brackets refer to the Bibliography.

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.

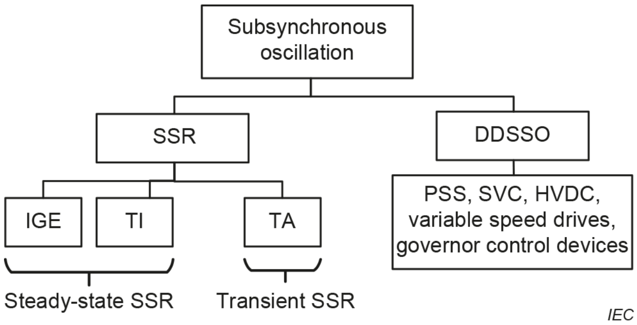

Figure 3 – Terms and classification of SSR by IEEE [13]

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].

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.