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# Subsynchronous Oscillation and Advanced Analysis: A Review

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**ABSTRACT** Subsynchronous oscillation (SSO) is classified as subsynchronous resonance, torsional interaction, or control interaction, depending on which devices or controllers are involved. Researchers have conducted numerous studies and developed methodologies on how to analyze SSO cases in different types of power systems. For these diverse mechanisms, complicated systems, and analytical methods, the overall summary and categorization of the SSO phenomena have been crucial, and numerous reviews have been published to this end. However, with the emerging inverter-based and power-electronics-based devices, in addition to the high computational capability, more advanced analytical methods have recently been researched, and more general, up-to-date literature surveys are thus needed. This study reviews the various SSO types depending on the interaction mechanisms, before investigating a number of representative SSO events in terms of the devices. Following this, the study evaluates the existing cutting-edge methods for SSO analysis and compares them to ascertain the appropriate method for specific SSO types. The review provides distinct practical considerations for the analysis to simplify the entire procedure. Ultimately, this paper presents a summary of modern SSO-damping and mitigation methods for pragmatic insight and future perspectives for a reader when dealing with old and the latest power systems.

**INDEX TERMS** Subsynchronous control interaction, subsynchronous oscillation, subsynchronous resonance, subsynchronous torsional interaction.

## I. INTRODUCTION

Power system planners and operators must address the small-signal instability caused by subsynchronous oscillation (SSO). In general, SSO indicates an oscillation with a frequency of 5 to 55 Hz, when the fundamental frequency is 60 Hz, and is differentiated by low frequency oscillation, which occurs at around 0.5 Hz to 3 Hz [1]. SSO can endanger the operation of the entire power systems by causing instabilities and, hence systems' electrical equipment may be severely damaged. When SSO phenomena were initially observed, the main cause was the interaction between the electrical systems and generators [2], [3]. Depending on where the resonances occur, the conventional power system SSO can be categorized into various types, including subsynchronous resonance (SSR), subsynchronous torsional interaction (SSTI), and subsynchronous control interaction (SSCI) [4]. The SSO type must first be determined before an appropriate analysis method can be selected, thereby helping in identifying the category of oscillations and effective measures to be implemented.

Since the first SSO event of 1970 [3], many such events have been recognized and analyzed. For example, SSR events have occurred in 1970 at the Mohave power plant located in southern Nevada, USA, at the Navajo Project in 1976, in the USA, in 2011 at the Shangdu power plant in the inner Mongolia, China, and in 1978 at Cholla Unit 2 in northest Arizona, USA [3], [5]–[7], while an SSTI event occurred owing to the interaction between a power plant and a static var compensator (SVC) in Chester, Canada [8]. Following the

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SSO events involving the wind-type power plants of the Electric Reliability Council of Texas (ERCOT) area [9], SSCI has been investigated in numerous wind-generation sites.

Researchers began to have interest in SSO analysis after the Mohave coal-fired power plant in southern Nevada failed twice, who ultimately concluded that the root cause was the interaction between the turbine shaft and the series-connected capacitor within the range of subsynchronous frequencies [2], [4]. Frequency scanning, eigenvalue (EV) analysis, and electromagnetic transient (EMT) analysis [10] started to be widely used to determine SSO risk, with the various analytical methods seen as fundamental tools for application in many engineering domains. However, as power grid dynamics have become more complicated with the advent of inverter-based resources and power-electronics-based devices, advanced methodologies based on high computational capability have been developed.

Therefore, this study presents a review of SSO events in terms of the root causes and the existing state-of-the-art analytical methods. While recent studies have dealt with SSO [4], [11], [12], mainly covered SSO caused by wind turbine generators (WTGs). As noted above, a more general approach for the analysis of SSO in relation to the other emerging power systems with power-electronics-based devices and inverter-based renewable sources such as high voltage direct current (HVDC) converters, flexible AC transmission system (FACTS) devices, SVCs, and power system stabilizers (PSSs) must be addressed. Furthermore, the existing analytical approaches must be re-examined as are believed to have matured. This study also presents practical considerations that could help engineers and researchers to analyze real-time systems. Subsequently, this paper stipulates an outline of novel damping and mitigation methods of SSO.

The paper is organized as follows. Sections II and III describe various power system SSO phenomena and events, respectively. Following this, Section IV presents the widely used analytical methods, and Section V outlines the advanced techniques for SSO analysis. Section VI reviews the practical considerations for the analysis, and Section VII and VIII presents the mitigation and conclusions respectively.

## II. SSO TYPES

### A. SSR

The series-compensated capacitors in AC transmission lines enhance transient stability and increase the total load transfer capability of the power system [4]. However, these capacitors can cause SSR problems and shaft failures because of the interaction between the capacitor and the turbine generators, meanwhile power plants with a long generator shaft are particularly vulnerable. The SSR occurs if the difference between the electrical resonance frequency, $f_{er}$, and the synchronous frequency, $f_0$, (complementary frequency $f_{sub} = f_0 - f_{er}$) matches the frequency of the rotor oscillation [13]. When the line compensation level increases, the resonant point moves toward the system frequency (e.g., 60 Hz), exposing the power plant to potential SSR problems. Two different types of SSR, namely induction generator effect (IGE) and torsional interaction (TI), are discussed below.

#### 1) IGE

This electrical phenomenon occurs when the rotor resistance negatively causes the unexpected growth of subsynchronous currents in the armature terminals [2]. When the rotor speed exceeds the rotating speed of the magnetic field generated by the current with an SSR frequency, the rotor resistance becomes negative, resulting in the self-excitation of the electrical system. Uniquely, IGE may occur in most types of power plants and power systems with a high series-compensation rate [4], [14].

#### 2) TI

TI relates to the electrical and mechanical interplay between a shaft system and a series-compensated electrical network [2], [4], [15]. Here, the generator rotor oscillation builds up when the induced subsynchronous frequency in the turbine generator becomes almost equal to one of the natural oscillatory modes of the turbine generator shaft. Compared with IGE, TI is likely to occur in a thermal plant with a long shaft, while it never occurs in hydropower plants due to the relatively large inertia of the turbine and because the gas-turbine generator has low SSR risk since its coaxial compressor operates and gas flows even in a no-loading condition [16].

### B. SSTI

This is a device-dependent phenomenon involving the interaction between the mechanical/torsional masses in a generator (or wind turbine) and the power-controlling devices such as HVDC converters, FACTS devices, SVCs, wind turbine control systems, PSSs, high-speed governor controls, and variable speed drive converters. Among the various power-electronic-based devices, HVDC converters and SVCs are typically vulnerable to SSTI.

#### 1) HVDC

The disturbance at the generator rotor induces both magnitude and angle-phase stator voltage oscillation, the latter causing the vibration of the firing angle of the HVDC rectifier, while the former affects the DC generation. Consequently, the electrical torque of the generator starts oscillating, and when the shaft speed is out of phase with the torque, the oscillation grows [17]. This interaction mechanism has been found in a current-source-converter (CSC)-based HVDC. Meanwhile, studies on general voltage-source converter (VSC)-based [18] HVDCs and modular multilevel converter (MMC)-based VSC-HVDCs [19] indicate that both can cause SSTI.

#### 2) SVC

This device is a power converter that can provide re-active power and can protect the power line against dynamic power oscillations through the supplementary modulation control.

**TABLE 1.** Device-Dependent Classification.

| Device | SSR-TI | SSR-IGE | SSTI | SSCI | Ref. |
|---|---|---|---|---|---|
| Synchronous generator | ✓ | ✓ | ✓ | X | [2], [4], [14], [15], [18], [19] |
| Wind generator (type 1) | X | ✓ | X | X | [26] |
| Wind generator (type 2) | X | ✓ | X | X | [27], [28] |
| Wind generator (type 3) | X | ✓ | X | ✓ | [29]–[31] |
| Wind generator (type 4) | X | X | X | ✓ | [32] |
| HVDC | X | X | ✓ | X | [18], [19], [33] |
| Series compensated capacitors | ✓ | ✓ | X | X | [2], [4], [14], [15] |
| SVC | X | X | ✓ | ✓ | [8] |

The symbol '✓' indicates 'vulnerable' while 'X' does 'invulnerable.'

However, SSTI may occur when an SVC is installed close to a power unit [8], as the control response of the SVC voltage regulator decreases the damping of torsional oscillations. Consequently, the electrical torque will be unstable, injecting torsional vibrations to the rotor. The SSTI risk increases if the generator's real power output, the tie power flow, or the SVC's reactive power output increases [8], [20].

#### 3) PSS

The PSS can dampen rotor-system oscillation at a low frequency of 0.1-2.0 Hz. However, PSS can also excite shaft torsional modes by injecting one or more oscillatory signals into the generator field windings [2], which are determined by feedback signals and the PSS parameters.

### C. SSCI

Much like SSTI, SSCI is also a device-dependent phenomenon, but involves the interaction between the power electronics control system and other devices, such as the series-compensated transmission line [4]. A negative resistance of the turbine at subsynchronous frequencies is induced, causing SSO instability. If the system is unable to dampen the SSO, the generators could be severely damaged [9], [21]. Basically, the oscillation produced by SSCI spreads faster than that caused by SSTI and SSR [22] owing to the fast response of the controller. SSCI incidents have frequently occurred in a doubly-fed induction generator (DFIG)-based type-3 WTG. However, SSCI can still occur in zero series compensation systems [23]. This oscillation is attributed to the interaction between the AC transmission system and the DFIG [24] or the direct-drive permanent magnetic synchronous generator (PMSG) [25].

### D. DEVICE-DEPENDENT SSO CLASSIFICATION

The above sections explained various SSO phenomena depending on which two systems interact with each other, and the device-dependent SSO classifications are presented in Table 1. This classification will help identify the appropriate method and tools for analysis when a specific device is installed in a grid.

## III. SSO EVENTS

Numerous SSO events have occurred where the responsible core devices differed. The following subsections describe representative SSO events based on the core device, with a summary presented in Table 2.

**TABLE 2.** Major SSO Events.

| Year | Location | SSO Type | Severity | Reference |
|---|---|---|---|---|
| 2015 | Hami | SSCI | Failure | [25], [34], [35] |
| 2012 | Guyuan | SSR, SSCI | Failure | [36], [37] |
| 2011 | Shangdu | SSR | Test | [4], [6], [38]–[40] |
| 2009 | ERCOT | SSR, SSCI | Failure | [9], [21], [41]–[44] |
| 1987 | Chester | SSTI | Test | [8], [20], [45], [46] |
| 1983 | Ontario | SSTI | Test | [47] |
| 1980 | Square Butte | SSTI | Test | [17], [19], [48], [49] |
| 1978 | Cholla | SSR | Test | [7], [50], [51] |
| 1976 | Navajo | SSR | Test | [5], [52], [53] |
| 1970 | Mohave | SSR | Failure | [2], [3], [13] |

### A. SERIES-COMPENSATED CAPACITORS

The Mohave coal-fired power plant encountered two consecutive shaft failures in 1970 and 1971 [2], [3], [13]. Following extensive analysis, the root cause of the incidents was found to be an excessive torsional interaction between the turbine generator and the series-compensated capacitors. The electrical resonance at 30.5 Hz excited a torsional mode at the 30.1 Hz frequency [3].

Following these incidents, SSR analysis for the Navajo Project was jointly conducted by the Arizona Generating Plant, the Arizona Public Service Company, the Los Angeles Department of Water and Power, and the Nevada Power Company [5]. The attendant frequency scan studies found a negative resistance in the 500-kV transmission system, which resulted in IGE [52]. The SSR test for the Navajo Project was completed in early 1976 and involved appropriate protection and countermeasures [53], including the installation of static blocking filters adjusted to natural frequencies to block the line current under torsional frequencies and to prevent the possibility of any resonant point within the subsynchronous range.

In 1978, the 345-kV series-compensated system of Cholla Unit 2 experienced TI and torque amplification [7]. To reduce the transient torque, pole-face amortisseur windings [51] and a reduced sparkover gap setting [50] were employed. The technical evaluations indicated that the installation of a SSO relay was a reliable solution for the SSR problem at the Cholla power plant.

Shangdu power plant's steam-turbine generators with a 45% fixed series-compensation experienced severe SSR problems [6], [38]. The countermeasure involved a supplementary excitation damping control (SEDC) method with torsional stress relay (TSR) [6]. However, after the compensation level was increased to deliver more power generation for the newly installed power plant, the existing SEDC and TSR could no longer protect the system against the SSO. Hence, a new combined scheme involving a generator terminal subsynchronous damping controller and SEDC was developed and deployed [39], [40].

### B. WTGs

In 2009, an SSO event occurred at the wind power plants of the ERCOT area [9]. The growth of the oscillations above two per unit led to severe damage to the crowbar circuits and the transmission facilities. The main cause for the oscillation was found to be the interaction between a type-3 wind farm and the series-compensated capacitors installed to increase the load-carrying capacity of the transmission line [21], [41]–[44]. The subsequent investigations revealed that both IGE and SSCI contributed to the ERCOT event, with the IGE causing self-excitation and the SSCI weakening the system damping under subsynchronous frequencies. WTGs are immune to SSTI on account of their large inertia owing to the heavy generator shaft and blades. In 2012, similar severe events occurred at Guyuan [36], [37].

As these events demonstrated, type-3 WTGs with series-compensated capacitors are susceptible to SSO problems. Although type-1 and type-2 WTGs can experience IGE, the SSO in type-3 WTGs is exacerbated by SSCI. Meanwhile, while it was generally held that type-4 WTGs did not have SSO issues as the power converters entirely separate the induction generator and the transmission systems, recent incidents and studies have demonstrated that they can be susceptible to SSCI, with the Hami event of 2015 revealing that the type-4 WTG can interact with weak AC systems [34], [35].

### C. HVDCs

Five months after starting the commercial operation at Square Butte in North Dakota, SSO field tests were conducted, revealing that the HVDC converter controls (i.e., the rectifier current control loop and the frequency-sensitive power control) excited the 11.5-Hz torsional modes of the turbine generator [48]. Unlike the ERCOT event, the Square Butte event involved an SSTI caused by the control interaction with the generator shafts. As countermeasures, a supplementary subsynchronous oscillation damping controller was developed and the current control transfer function was modified [17], [49]. This event ultimately led to widespread interest in SSTI and subsequent studies on SSTI-related mitigation and protection.

### D. SVCs

In 1990, SVCs were installed in the 345-kV power trans-mission line of the Maine Electric Power Company at Chester, Canada to enhance the transmission capacity of the HVDC interconnections [45], [46]. Prior to the installation, an investigation into the possibility of undesirable vibration found that SSTI could occur in such a way that an SVC voltage regulator would reduce the damping of the torsional modes of the nearby turbine generators. Control filters were thus installed to resolve the torsional stability issue.

### E. GOVERNORS

In 1983, when commissioning a nuclear unit at Ontario Hydro, a torsional oscillation caused by a speed electro-hydraulic governor characterized by high-gain electronics and high-pressure oil systems was observed [47]. Anomalous vibrations were ob-served for the first time in the system when the nuclear power generation unit had a load level of 100 MW. For migration, the phase load was changed and valve circuits were linearized. However, severe oscillations were again detected when the load level surpassed 475 MW, with a mechanical resonance of around 22 Hz caused by a large spring on the governor valve. The governor valve was extremely imprecise at load levels above 475 MW owing to the rapid increase of the governor-loop gain. A more precise linearized circuit with notch filters effectively eliminated these torsional oscillations, successfully allowing the unit to operate at full-load capacity.

## IV. SSO ANALYSIS METHODS

The section presents the fundamental SSO analysis methods widely employed in both research and practice, followed by two general approaches to using the methods for SSR and SSTI analysis.

### A. FREQUENCY SCANNING METHOD (FSM)

In terms of SSR, the network impedance of subsynchronous components determines the resonance frequency (i.e., $f_{er}$), which may result in SSR when its 60-Hz complementary frequency is very close to the rotor oscillation frequency. FSM is a method that can compute the impedance using the line parameters [54]. However, it considers only the grid impedance, and not the mechanical shaft system or the control system. Therefore, its accuracy is relatively lower than that of other more detailed methods, and FSM is typically used as a primary scanning method before detailed analysis is conducted.

The FSM evaluates the electrical damping of each torsional mode $\sigma_{en}$, which can be independently calculated through mode decoupling [54], [55]. Practically, mechanical damping $\sigma_{mn}$ is assumed to be zero or approximately 0.002 $f_n$ because the values are virtually impossible to determine without a field test, which also cannot always provide the true damping value [56]. The assumption of $\sigma_{mn} = 0$ is usable from a conservative point of view. As shown in [55], total damping of the $n$th torsional mode is given by

$$\sigma_n = \sigma_{en} + \sigma_{mn}, \tag{1}$$

noticing that $\sigma_n < 0$ indicates high SSR risk.

FSM can also indicate potential SSR-IGE in terms of whether there is negative resistance at the zero-crossing frequency of a reactance. However, this requires at least one EMT test verification for reliable results. Moreover, FSM can be applied to SSR analysis in relation to transmission systems with thyristor-controlled series capacitors (TCSCs) because a TCSC can be expressed as an apparent impedance, which continues during normal TCSC operation [57].

### B. UNIT INTERACTION FACTOR (UIF) CALCULATION

FSM, which essentially depends on line impedance, can-not be applied to control-system-related SSO phenomena such as SSTI. Thus, the UIF method has been used as an alternative method for the primary screening of potential SSTI risk near HVDC stations [58]. This method gauges how much a generator unit contributes to the energy interplay with an HVDC by observing the unit's short-circuit capacity contribution at an HVDC bus. The UIF of the $i$th generation unit in [58] is calculated as follows:

$$UIF_i = \frac{MVA_{HVDC}}{MVA_i}\left(1 - \frac{SC_i}{SC_{TOT}}\right)^2, \tag{2}$$

where $MVA_{HVDC}$ represents the HVDC rating, $MVA_i$ the rating of the $i$th unit, and $SC_i$ and $SC_{TOT}$ are the short-circuit capacity at an HVDC commutation bus excluding and including the $i$th unit, respectively. Quantitatively, if $UIF_i$ is greater than 0.1, there is the likelihood that the interaction between the $i$th unit and the HVDC will lead to SSTI, and this therefore requires more detailed SSO analysis tools than basic screening tools [48].

### C. EIGENVALUE (EV) ANALYSIS

Based on the ordinary set of linear differential equations representing the entire system under study, EV analysis investigates small-signal stability for multi-machine power systems within a wide range of frequencies [59]. This method can provide detailed information on the frequencies, damping coefficients, and small-signal-stability in all modes and can be used for designing damping control. Practically, EV analysis can be used in the study of all types of SSO; however, its actual implementation is not readily available because the dynamic models for all components of the entire system should be prepared and merged, but the manufacturers rarely develop their own control designs or detailed dynamic models accessible.

Mathematically, system dynamics can be represented by a set of linear ordinary differential equations as follows:

$$\dot{x} = Ax + Bu, \tag{3}$$

where $x$ and $u$ indicate state and control variables, respectively, and the matrices $A$ and $B$ contain coefficients. Then, the eigenvalues are computed by

$$det(A - \lambda I) = 0, \tag{4}$$

where $det$ indicates the determinant of a matrix, $\lambda$ the eigenvalues, and $I$ the identity matrix.

Following the EV computation, if an eigenvalue within the subsynchronous frequency range contains a positive real part, the damping at the frequency is negative, indicating that there would be high potential SSO. For example, a system associated with TI may have torsional-mode eigenvalues containing a positive real part, while a system suffering from IGE may have electrical-model eigenvalues with a positive real part.

To perform EV analysis, all the models, including the generators, turbine shafts, transmission lines, control systems, and power electronics, must have linear equations. However, power-electronics-based devices display nonlinearity and have high-frequency switching operations, and the model must therefore be linearized for EV analysis. However, the linearization of nonlinear models induces some inaccuracy, requiring a compromise between analytic depth and accuracy from engineering perspectives.

### D. EMT ANALYSIS

In pursuance of the simplicity and rapidity of SSO study, FSM is suitable for primary screening purposes and facilitates the process to obtain a list of cases under SSO risk. However, SSO is affected by many factors, including the network topology, the generator operating conditions contingency, device and control parameters, and the compensation level, all of which are not fully reflected in FSM. Meanwhile, although EV analysis provides detailed and informative results than FSM, nonlinear models must be linearized for EV computation. As such, EMT simulation must be performed for the high SSO-risk cases in the list screened through FSM. The EMT simulation for SSO analysis must involve a consideration of the electromagnetic dynamics of the transmission systems as well as the extremely short time constants in the order of microseconds. While EMT analysis is the most accurate method, a sophisticated EMT-level model is expensive, meaning this method is generally used to validate the results obtained through FSM and EV analysis.

Contrary to EV analysis, the EMT method can simulate both nonlinear and switching devices without model simplification, which guarantees the accuracy and efficiency of SSO studies. Nevertheless, the simulation requires a long time owing to detailed models. To overcome this drawback, a real-time simulator (RTS) that has high computational capability can be used, while the RTS was initially designed for a hardware-in-the-loop (HILS) test.

### E. GENERAL APPROACH OF SSR ANALYSIS

Topology screening, frequency scanning, and detailed analysis with EV computation and EMT simulation are three general steps in any SSR study framework [60]. Topology screening identifies $N - x$ contingency sets causing a radial connection between the generator and the series capacitors using the classic Ford-Fulkerson max-flow min-cut theorem. When the number of contingencies (i.e., $x$) is larger than a pre-determined threshold, it can be concluded that the system is under no SSR risk. In all other cases, FSM should be performed in terms of the contingencies (from $N - 1$ to $N - x$). Then, for contingencies demonstrating negative damping, EV and EMT analyses are required. The EMT simulation applied to the entire system or to the regional system is fairly complicated and time consuming. However, as the number of contingencies for assessment is reduced through the pre-screening methods (i.e., topology and frequency scanning), the time scale also reduces while maintaining both the accuracy and efficiency.

### F. GENERAL APPROACH OF SSTI ANALYSIS

Similar to the general approach of SSR analysis, SSTI potential is generally assessed using three steps: pre-screening; formal screening; and detailed EMT simulation. The pre-screening considers the type and size of the machine, the electrical proximity of the HVDC system, and the system topology to determine where there is an SSTI risk with the HVDC system and turbine generators without an in-depth analysis. In general, hydro-electric turbine generators and gas-turbine generators may be screened at this stage, but the following stage must be initiated in the case of steam-turbine generators. Following the initial screening, the second step covers a wide range of possible systems, including normal and contingency conditions. As the formal screening for SSTI, the UIF is calculated to ascertain how closely coupled a turbine generator and HVDC system are. For a turbine generator with a UIF value of 0.1 and above, a more detailed SSTI study is required, and a more detailed representation of the controllers and device models must be prepared to test or validate the SSTI possibility due to disturbance. EMT simulation in the time domain is suitable for testing the impact of disturbance or small-signal perturbation in the detailed analysis. All three steps should be performed attentively to ensure an accurate assessment of the potential SSTI.

## V. ADVANCED TECHNIQUES FOR SSO ANALYSIS

The methods described in section IV are the fundamental tools for SSO analysis. However, it is often challenging to put these methods into practice due to large and complicated transmission networks, unknown model information, and power-electronics-based devices with high nonlinearity and fast dynamics. In view of this, the following subsections present the more advanced techniques for SSO analysis.

### A. TWO-AXIS ANALYTICAL FSM

Based on a d-q axis representation, this advanced technique uses complex torque coefficients to scan the SSR risk in a given system [13]. The effective damping constant of the $n$th torsional mode, $D_n$, was obtained in [13] as follows:

$$D_n = D_e + D_m = 4H_n\sigma_{en} + 4H_n\sigma_{mn}, \tag{5}$$

where $D_e$ and $D_m$ represent the electrical and mechanical damping constants, respectively, $\sigma_{en}$ the electrical damping, $\sigma_{mn}$ the mechanical damping, and $H_n$ the modal inertia. When $D_n < 0$, it can be concluded that the SSO has deteriorated [61].

Meanwhile, the electrical and mechanical complex torque coefficient, $k_e(j\lambda)$, $k_m(j\lambda)$ are combined together to form an equation $[k_e(j\lambda) + k_m(j\lambda)]\overline{e} = 0$ which governing the oscillation. SSR problems may occur if $K_e + K_m$ approaches zero [62]. Two-axis analytical FSM can be used to calculate complex torque coefficients in any network but requires the impedance matrix values of the entire network, which are difficult to obtain using d-q coordinates, even for a simple network [63]. Frequency scanning of up to double the nominal frequency is generally carried out to obtain the network impedance values at the subsynchronous and supersynchronous frequencies, which are used to calculate the external impedance matrix. The obtained impedance matrix can then be easily used to obtain $K_e$ and $D_e$, which is a crucial step in determining the presence of SSR.

Compared to basic FSM, this method requires more detailed machine data, which makes it more demanding. However, it is more precise as it takes the influence of the generator operating point on the electrical damping into account, while it can only be used to scan SSR-IGE and SSR-TI, and not the other types of SSO.

### B. TEST SIGNAL METHOD

The test signal method, also known as the complex torque coefficient method, involves the use of time domain simulation software to model the electrical power system [13], [58]. Hence, one of the merits of this method is that the detailed and nonlinear models, including power electronics devices, can be incorporated within the SSO analysis, which ensures highly credible analysis results.

The process involves identifying the unknown torque coefficients, $K_e$ and $D_e$, from equations in [13] representing the electrical torque as follows:

$$\Delta T_e = K_e \Delta\delta + \frac{D_e}{\omega_o}\Delta\omega, \tag{6}$$

where $\delta$, $\omega$, and $\omega_0$ denote the electrical angle of a machine, the rotor speed of the machine, and the nominal speed, respectively. Using a recursive least square (RLS) algorithm, (6) can be solved to yield the unknown coefficients, which are given as:

$$K_e = \frac{-\Delta T_y}{\Delta\hat{\delta}}, \quad D_e = \frac{\Delta T_x \omega_o}{\Delta\hat{\delta}\Omega}, \tag{7}$$

where $\Omega$ is the modulation frequency, and $\Delta\hat{\delta}$ is the Fourier resolution of $\delta$. $\Delta T_x$ and $\Delta T_y$ are the real and complex parts of the complex phasor of the oscillating component $\Delta\overline{T}$, respectively, which can be obtained through a RLS algorithm; $\Delta\overline{T}$ is the phasor of the total mechanical system torque viewed as a mass-spring-damper system.

In the time domain simulations with the test signal method, test signals are injected into the rotor of the generator under investigation [64]. The simulation must be performed at a steady state to obtain the electromagnetic torque, power angle, and angular velocity, the Fourier resolution values of which in different frequencies are used to calculate the damping torque coefficient. The system is deemed to be stable if the damping torque coefficient is positive and vice versa. Unlike the two-axis FSM method, this method does not require the mechanical damping values to determine the SSO-related instability of the system.

### C. DYNAMIC FSM

This method is a suitable analytical method for SSCI in terms of wind power plants. It involves the use of a detailed time domain representation of the wind turbine model with taking the turbine nonlinearity and its active behavior into account [22]. With this technique, a small signal of voltage or current is injected on the steady-state excitation of the system before the harmonic impedance of the wind turbine generator is determined. Typically, the voltage injection creates a smaller disturbance on the operating point of the system and has the advantage of reducing the necessity for a trial and error approach by lowering the degree of sensitivity. Nonetheless, the current injection scanning is accurate and captures the impact of other dynamic devices on the system side as well as that of all the complex controls and mechanical shaft systems on the turbine side [65].

Generally, either current or voltage can be superimposed onto the system as the excitation signal, which ultimately yields the apparent resistance and reactance of the turbine across the subsynchronous frequency range. As a result, the resistance and reactance are utilized for the turbine-side scans. In [42], four techniques, frequency scan, short-circuit calculation in terms of the frequency-dependent network, frequency-scaling of the equivalent network derived, and network reduction, were used to check the presence of crossover points in conjunction with the turbine side by scanning the reactance at the driving point, with the crossover point an indication of potential SSCI concerns. The use of dynamic FSM in tandem with EMT analysis can help to identify the risk of SSCI in wind power plants and saves a great deal of time compared with using EMT analysis alone [22].

### D. NETWORK EQUIVALENCING METHOD

For accurate SSO analysis, all the transmission line inductors and capacitors must have variable states, unlike with power flow analysis. EV or EMT analysis of the entire power system is practically impossible given the finite computer memory. Hence, the area of interest that, even with a small change, has potential SSO risk, should be carefully selected such that any bus impedances within the area must be maintained within the subsynchronous frequency range despite the equivalencing [66]. The identification of the area of interest is carried out using a metric known as the damping sensitivity index (DSI), which is the derivative of the electrical damping on the impedance parameter a. Mathematically, in [66], the DSI is given as

$$DSI = \frac{\partial \sigma_{em}}{\partial a}. \tag{8}$$

The DSI thresholds must be selected and categorized for the critical, subcritical, and non-critical sets, which should, theoretically, be small enough to ensure the accuracy of the network equivalent model. Finally, if all the DSIs are smaller than the thresholds of the subcritical set, the area of interest or study zone can be determined. As such, network equivalencing of the whole system that excludes the area of interest area can be easily formed, which ensures greater accuracy and shorter computation times than if using the entire system.

Several network equivalencing methods, including Thevenin (Norton), mutual impedances [67], and frequency network-dependent equivalencing (FNDE) [68], can be utilized to find an equivalent model of the large system using DSI. At low power frequencies, Thevenin or Norton equivalencing is a highly recommended accurate method for the equivalencing of a simple linear network. However, it is advised to use other equivalencing approaches such as FNDE, which can actively respond to the changes of the external network once a network is complicated and contains elements with extensive models such as power transmission lines, since the Thevenin or Norton approach becomes less accurate under these conditions. This method uses the reactance obtained via dynamic frequency scanning.

### E. IMPEDANCE NETWORK MODEL (INM)

The established impedance models of power generators, transmission lines, and transformers are interconnected based on the system topology and the power flow data of a specific operation condition to form the entire INM [69], [70]. Once the INM is obtained, the lumped impedance can easily be calculated according to the impedance aggregation. The impedance-frequency curve of the lumped impedance is used for determining the SSO stability. Here, a system is unstable if the slope of the reactance is positive and the resistance is negative. Furthermore, abundant information that can help to calculate the damping and frequency of SSR can be found at the zero-crossing point of the curve. However, in practice, small-signal INM is used for SSR analysis in terms of power systems with regular changes in the number of online operating generators and control parameters, and varying turbine speeds [71]. The impacts of these variations are taken into account during the analysis based on small-signal INM, which ensures both the accuracy and availability of the information on SSR damping that is outside the capacity of normal INM.

### F. OPEN-LOOP MODAL ANALYSIS

This method is used to study SSO in relation to multi-machine characterized power systems through obtaining a pair of open-loop SSO modes that are likely causing the instability in the system [72]. Under an open-loop modal resonance related to the condition when the system has an open-loop SSO modes pair, the machines contributing to the SSO can be identified after calculating the participation factors.

The calculation of the power system and generator SSO modes according to their respective open-loop matrices is per-formed to obtain complex eigenvalues. Here, the power system is deemed as unstable when the real part of the complex eigenvalues of the SSO modes are positive. However, even if the SSO mode values are found to be negative, the system cannot be definitively regarded as stable. Thus, a computational index known as the modal resonance index (MRI) is introduced to identify any SSO risk. The SSO modes and their residues are used to calculate the MRI value, which, when found to be positive, indicates that the system is at risk of SSO. Much like with FSM, this method can be applied to the open-loop subsystems based on the closed-loop model [24]. Moreover, the possibilities of SSO risk can be evaluated due to the VSC-HVDC line under system modal conditions.

### G. OSCILLATORY STABILITY CRITERION (OSC)-BASED INM

Based on unified *dq*-frame INM, this method provides an option for evaluating the oscillatory stability of the original system simply through analyzing the impedance-frequency curves of the determinant of the lump matrix [34]. The stability can be evaluated through analyzing the characteristics of the lumped impedance matrix, which is traditionally associated with zero-based zero-crossing points (ZZPs). Here, the oscillatory stability is judged according to two criteria based on equivalent resistance and reactance curves.

The first criterion relates to whether there are a pair of conjugate zeros corresponding to a ZZP on the reactance curve. The stability of the target system can be determined according to the product of the resistance and the slope of the reactance at the ZZP. An oscillatory mode will be unstable if the calculated product is found to be negative, and vice versa. The second criterion relates to whether a zero-crossing point corresponding to a pair of conjugate zeros is present in the equivalent resistance curve but absent in the reactance curve. Similar to the first criterion, the product of the reactance and the slope of the resistance at the ZZP determines the system's stability. However, a negative product indicates that the oscillatory mode is stable, and vice versa.

### H. ARTIFICIAL INTELLIGENCE (AI) BASED ANALYSIS METHOD

As addressed above, one of the momentous challenges in evaluating SSO problems is the nonlinear characteristic of power systems. Nevertheless, with the advancement of technology and the help of artificial intelligence (AI), researchers can reduce the entire process without compromising accuracy, performance, and cost.

An AI-based SSO analysis techniques can solve the nonlinearity of power systems through the wavelet transform and artificial neural network (ANN) [73]. A recurrent neural network (RNN) is a present-day ANN suitable for dynamic power systems that can attain critical conditions such as the relationship between the generator unstable mode and time. This method uses the continuous wavelet transform to solve the critical time-frequency utilizing convolution between continuous signal and B-spline that is also identified as mother wavelet to inspect generator speed fluctuations to detect SSR.

Machine learning (ML) models like support vector machines, XGBoost, and random forest exhibit an accuracy of more than 95% in spotting SSR in power systems [74]. ML models utilize features like the variation in angular velocity and the fluctuation of torque angle in a learning stage at distinctive operating circumstances. ML analysis techniques are convenient for real-time operations and consume less time during the SSR study phase.

Another AI-based analytic technique adopts synchrosqueezing wavelet transforms (SWT) jointly with K-means clustering to detect all categories of SSOs in the system [75]. The SWT verifies whether SSO exists or not and ascertains the number of vibration modes before K-means clustering determines the precise frequency of those modes. This method is profoundly efficient because it can separate and mitigate oscillation modes followed by detecting modes parameters adopting slice examination and Hilbert transformation.

## VI. PRACTICAL CONSIDERATIONS

### A. COMPARISON OF ANALYSIS METHODS

In analyzing power system SSO problems, it is important to choose an appropriate analysis method for the specific SSO type. Here, while the EV, EMT, test signal, open-loop modal, and network equivalencing methods can be used to study all types of SSO, FSM, INM, and oscillatory stability criteria methods are limited to SSTI cases because the methods are based on network impedance, and the interactions with the HVDC or power electronics controller cannot appear in the apparent impedance.

The general approaches described in sections IV-E and IV-F involve procedures that simplify the entire analytical process of explicit SSO categories such as SSR, SSCI, and SSTI. Similarly, the UIF, dynamic FSM, and two-axis analytic methods are typically used for a distinct type of SSO problem. The dynamic FSM method is strictly applicable to SSCI analysis related to WTG-based systems because this method involves the determination of the harmonic impedance. Here, the calculations are only valid when there is generation of the subsynchronous inter-harmonics that can only be produced by WTGs due to the unbalanced voltage supply and the over-modulation of the PWM converters [22]. Meanwhile, the two-axis FSM method requires linearized equations of the multi-mass shaft system of the turbine generator and the perturbations in the generator rotor angle and mechanical torque to evaluate the torsional dynamics

[13], [61], [62]. Thus, the two-axis method is clearly unsuitable for evaluating SSO types other than SSR-IGE and SSR-TI since these do not involve the interaction of the turbine generator's multi-mass shaft system.

Overall, it is important to note that there is more than one method for analyzing any single SSO type. The relative complexity and timescale, as well as the economic factors, play a vital role in determining the most suitable method of analysis. Table 3 summarizes the comparison of all the SSO analysis methods discussed in this paper.

**TABLE 3. Comparison of Analysis Methods.**

| | SSR -IGE | SSR -TI | SSTI -HVDC | SSTI -Others | SSCI |
|---|---|---|---|---|---|
| FSM | O | O | X | X | O |
| UIF | X | X | O | X | X |
| EV | O | O | O | O | O |
| EMT | O | O | O | O | O |
| Two-axis analytic FSM | O | O | X | X | X |
| Test signal method | O | O | O | O | O |
| Dynamic FSM | X | X | X | X | O |
| INM | O | O | X | X | O |
| Open-loop modal | O | O | O | O | O |
| OSC-based INM | O | O | X | X | O |
| Network equivalencing | O | O | O | O | O |

The symbol 'O' indicates 'applicable' while 'X' does 'not applicable.'

### B. OTHER GENERATOR TYPES

In SSO analysis, many factors must be considered, including the generator type. Generators such as hydro generators and combined cycle gas turbines (CCGTs) have not yet exhibited a risk of SSO in either simulations or real-life events [16]. Hydro generators cannot interact with the network at the torsional frequency due to their low mode shape and high mechanical damping capability. Similarly, CCGT generators have mechanical damping that is both positive and small due to the significant amount of gas flow at both the turbine and the compressor stages under both full-load and no-load conditions. Recently, power industries have begun to pay attention to type-4 wind generators. No clear case of SSO involving such generators has yet been observed in practice, while simulations performed on plants consisting of this generator type, including the Hami power station in China, have indicated the presence of SSO [25], [34], [35].

## VII. DAMPING AND MITIGATION METHODS

Proper protection must be selected and implemented to maintain stability and prevent device damages and personal injuries. Notwithstanding, the preceding sections facilitate engineers to observe the definitive SSO classification, which is indispensable before enforcing damping and mitigation methods to the power system to avert the recurrence of this problem. The damping and mitigation techniques must be efficient and cost-effective by correlating the predicted cost of damage and protection. Existing SSO countermeasures like bypassing series compensation and tripping generators might not be cost-effective, and hence researchers have conducted studies on SSO mitigation methods. One must consider system composition, type, and situations when deciding these techniques. The following classifies advanced SSO damping and mitigating techniques based on power equipment [76]–[87]:

- Intelligently optimized multimodal supplementary excitation damping controller (OMSEDC)
- Static synchronous series compensator (SSSC)
- Static VAr compensator (SVC) (based on the genetic algorithm)
- STATCOM with a Fuzzy logic controller (FLC) and a proportional integrator and derivative (PID) controller
- Power oscillation damper (POD)

Furthermore, we can mitigate the SSO with more advanced approaches as follows [88]–[91]:

- Linear optimal control
- Motion-induction compensation (MIC) control
- AI-based mitigation techniques

### A. OMSEDC-BASED MITIGATION

Supplementary excitation damping controller (SEDC) is used to alleviate the SSO by the particle swarm optimization (PSO) [76]. This technique shifts the phase to match with the described angle criterion of the system even after torque fluctuation generated by series capacitor compensation has developed [92]. The dynamic signal analyzer has proven that the SEDC in a wide range of applications is practically efficient and economically friendly in mitigating SSO [93]. Conventional SEDC guarantees optimality and stability in only one operating condition. However, adopting an intelligently OMSEDC into a system determine optimality using the genetic and simulated annealing algorithm (GASA) in all operating conditions [86]. Comparably to GASA, the teaching learning-based optimization (TLBO) algorithm can also resolve an optimization complication and retrieve the oscillation damping controller criterion [87]. This robust SEDC (OMSEDC) makes SEDC practical and effective in damping and mitigating oscillations in series compensated power systems.

### B. SSSC-BASED MITIGATION

The SSSC is a contemporary mitigation strategy that compensates subsynchronous voltage to quench the SSCI, especially in PSMG-based wind farms [77]. The SSSC is a component of FACTS associated with the power system through a series transformer that can govern the power flow smoothly by instilling governable offset voltage into the power channel. Sub-synchronous components are added to SSSC as a supplementary signal to the primary voltage control signal to compensate for the point of common coupling (PCC) voltage when SSCI appears to develop in the system. The SSSC can mitigate SSCI conclusively in PSMG-based wind farms.

### *C. SVC-BASED MITIGATION*

The SVC is one of the FACTS controllers comprising thyristor controlled and switched reactors (TCR and TSR) adopted for damping SSR [78], [81]. This controller is usually installed at the center or any other convenient point of the power transmission line, accommodating series compensated capacitors to modulate voltage amplitude and alleviate oscillations in the system. However, the selection of SVC auxiliary controller specifications has to be done carefully, employing a genetic algorithm (GA) as introduced in [85] to damp all modes of oscillations. The SVC is practically and economically efficient and reacts very fast to SSR to prevent personal injuries or equipment damages in power systems.

### *D. STATCOM-BASED MITIGATION*

The STATCOM is another FACTS SSR-based mitigation device stationed at the generator bus to stabilize the system with a series of compensated capacitors by adjusting power and torque oscillations. This device has an advantage over other FACTS devices because it can alleviate the oscillations without controlling the level of compensation [84]. STATCOM majorly controls the reactive power by varying the voltage of the DC capacitor that has the size of energy storage similar to the instantaneous energy when oscillations happen. Modern STATCOM is more efficient in maintaining the generated DC capacitor voltage in phase with that of the system by deploying the service of a fuzzy logic controller (FLC) and proportional integrator and derivative controller (PIDC) [79], [82]. These controllers require lesser mathematical computations even for non-linear systems and minimize error when STATCOM responds to the oscillations.

### *E. POD-BASED MITIGATION*

The POD is an SSCI mitigation means that installs small shunt impedance between series capacitors compensated transmission line and a generator. The active power of the generator is used as input to provide a supplementary controller with an output signal. The residue technique grants appropriate specification selection of POD supporting compensation of the line for more than a 90% degree while guaranteeing security [80]. This technique corrects the eigenvalues to their designated stability point. This method waives the effects of any steady-state value of the input signal, determines and equips the damping desired to mitigate SSCI. Additionally, the POD damps oscillations that are associated with enormous fault-based vibrations [83].

### *F. LINEAR OPTIMAL CONTROLLER*

The linear optimal controller is a device invented for damping SSO emerging from the negatively damped modes [88]. The eigenvalues analysis method serves to attain damping modes of oscillations. The linear optimal controller creates appropriate damping for torsional modes by transferring eigenvalues of the state matrix to the left-hand side of an s-plane when the real part of eigenvalues has positive values. The method grants degree of stability by utilizing a control signal that decreases the performance index.

### *G. MIC CONTROL*

As specified in section VI-B, there is no SSO incident in type-4 wind generators up to date because it can eliminate the negative resistance [89]. The MIC controller makes type-3 to operate similarly to wind type-4 by aborting its intrinsic dynamics without deteriorating power quality or retarding dynamic response. The origin of SSCI in type-3 generators is motion induction amplification that induces negative resistance in the system. The technique compensates for the amplification via control installed in the rotor-side convertor. The MIC is independent of the parameters of a series-compensated line but depends on the parameters of the generator and still maintains the current control functions.

### *H. AI-BASED MITIGATION TECHNIQUES*

An adaptive neuro-controller is an AI-based device invented by utilizing real-time recurrent learning (RTRL) algorithm and trained by the neural network (NN) to regulate the firing angle of the thyristor controlled series capacitor (TCSC) [90]. TCSC reacts to the variation in mechanical torque when SSR develops in the system to adjust the output and damp the oscillations. This method is convenient for online operation and, a linearized model is non-compulsory even for non-linear systems.

Intelligent power oscillation damper (iPOD) is another AI-based alleviate technique that debilitates electromechanical inter-area oscillation [91]. This damper is deployed with a synchronous power controller (SPC) to grant a supplementary source for damping vibration in a broad operating conditions range. The iPOD is a substitute for the ordinary power system stabilizers (PSS) that has phase lag and functions in a limited operating range.

## VIII. CONCLUSION

Along with the increase in power demand, power electronics devices are widely used in the systems and hence, instabilities caused by SSO continues to be a huge concern in power systems worldwide. At present, few studies have discussed SSO in terms of every type of power system and the corresponding method of analysis. This paper outlined the various types of SSO along with the corresponding events that occurred at various power plants. Here, it was highlighted how the Mohave event led to the awareness that it is impossible to protect electrical systems from SSO if the source is not well recognized. The SSO analysis process is essential in terms of mitigation since it is the primary source for the identification of the permanent technical solutions as well as the economic considerations. The paper also introduced a number of practical considerations for the analysis, which will help readers to simplify the whole analytical process. Consequently, the source of interactions discovered through the analysis and other considered factors provide comprehensible insight into the mitigation process. More importantly, this work articulated new aspects for readers on SSO damping and mitigating techniques after meticulous analysis incorporated with the practical examination of the power systems.

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