energies

Review

Sub Synchronous Oscillations under High Penetration of Renewables—A Review of Existing Monitoring and Damping Methods, Challenges, and Research Prospects

Uvini Perera , Amanullah Maung Than Oo and Ramon Zamora *

Department of Electrical and Electronic Engineering, Auckland University of Technology (AUT), Auckland 1010, New Zealand
* Correspondence: ramon.zamora@aut.ac.nz

Abstract: With the recent developments in renewable energy generation and addition of power electronic devices, power system dynamics have become extremely complex. One of the challenges faced due to this transition is the sub synchronous oscillations caused by the interaction of renewable energy sources and various components of the power grid. Recently reported incidents due to sub synchronous oscillations highlight the need of monitoring and suppression of these harmful oscillations in real time. This paper gives an overview of the phenomena of sub synchronous oscillations and discusses the existing monitoring and damping techniques along with their limitations. Further, it highlights the research trends along this path.

Keywords: sub synchronous oscillation/resonance (SSO/SSR); distributed energy resources (DER); power electronic converter (PEC); wind turbine generator (WTG); phasor measurement unit (PMU); sub synchronous state estimation (SSE); artificial intelligence (AI)

check for updates

Citation: Perera, U.; Oo, A.M.T.; Zamora, R. Sub Synchronous Oscillations under High Penetration of Renewables—A Review of Existing Monitoring and Damping Methods, Challenges, and Research Prospects. *Energies* **2022**, *15*, 8477. https://doi.org/10.3390/en15228477

Academic Editor: Frede Blaabjerg

Received: 14 October 2022
Accepted: 8 November 2022
Published: 13 November 2022

1. Introduction

Owing to the ongoing transformation of the power grid towards sustainable development, power generation using renewable energy sources has been increased worldwide. The total addition of renewable energy globally in 2020 was more than 260 GW. This is greater than fourfold the addition from other sources and therefore depicts the trend of increased renewable penetration even during the adverse effects of the pandemic. Further, it is forecasted that the renewable energy penetration worldwide will increase significantly by 2050 [1,2].

Large scale development of wind energy for electricity production has become an integral part in many countries, with China ranking the first as having a total capacity of 221 GW power generated using wind energy. Furthermore, the United Nations Environment Programme (UNEP) has estimated that China has a potential of 1400 GW onshore and 600 GW offshore wind energy overall [3]. Eight 10 GW scale wind power bases are already implemented in different parts of China. The other leading countries deploying wind energy for power production are USA (96.4 GW), Germany (59.3 GW), India (35 GW), Spain (23 GW), UK (20.7 GW), France (15.3 GW), Brazil (14.5 GW), Canada (12.8 GW), and Italy (10 GW) [3,4]. In addition to wind, there has been a rapid increase in PV penetration in recent years. Several large-scale PV farms have been installed and most are connected to the transmission system, such as Longyangxia Dam Solar Park (850 MW) in China, Solar Star I and II (579 MW) in USA, Topaz Solar Farm and Desert Sunlight Solar Farm (550 MW each) in California, USA, Huanghe Hydropower Golmud Solar Park (500 MW) in China, Charanka Solar Park (345 MW) in India, Agua Caliente Solar Project (295 MW) in Arizona, USA, and California Valley Solar Ranch (250 MW) in California, USA [5].

The output generated from the abovementioned renewable energy sources is converted to AC with a frequency equal to that of the power system by utilizing power electronic devices. Hence, wind and solar photovoltaics are also referred to as inverter-based resources (IBRs) and are asynchronous. That is, IBRs do not have a physical coupling with the generated frequency, unlike the synchronous generators whose frequency of alternating current is physically coupled to the rotating shaft of the machine [6]. The ongoing transformation towards high renewable penetration has affected the power system dynamics to a great extent.

Power electronic converter (PEC) interfaced devices are deployed to account for the limitations that have arisen due to reduction in conventional synchronous generators. However, the presence of a power electronic dominated system leads to the control of interactions affecting the stability of the power grid. Emulation of synthetic inertia, frequency support, and grid synchronization are some such functionalities supported by PEC interfaced devices. The converter control system comprises of different control loops, such as current control, voltage control, power control, and phase-locked loop (PLL) [6–8]. In addition to the proliferation of PECs, factors such as intermittency of wind and solar irradiance, weak immunity to fluctuations in frequency and voltage, low short circuit ratio, reduction of inertia, and grid dynamics ranging over multiple time scales are the factors exacerbating the emerging stability issues [9,10]. An overview of the modern power grid is illustrated in Figure 1. The classification of power system dynamic stability has also been revised recently to incorporate the fast responses of PECs. Accordingly, two new classes of stability, namely resonance stability and converter driven stability, have been added to the traditional classification of rotor angle stability, voltage stability, and frequency stability [11,12].

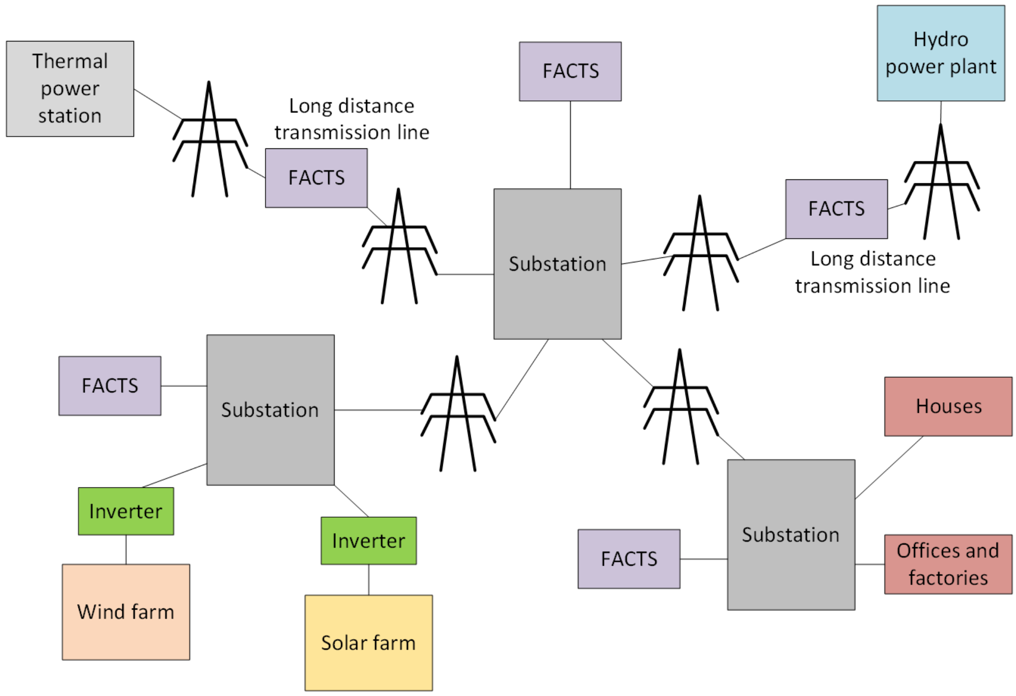

Figure 1. System level diagram of the modern power grid.

This review aims to focus on the sub synchronous oscillation (SSO) phenomenon. It is categorized under resonance stability in the revised power system stability classification. SSO can be described as a harmful condition where growing or sustained oscillations occur when the electrical network exchanges energy with two or more power system components at one or more of the natural frequencies of the combined system [13,14]. In the past, SSO has been observed in synchronous generators and high voltage DC (HVDC) systems. Research also demonstrates the potential risk of SSO in flexible AC transmission systems (FACTS). The first sub synchronous oscillation incident was reported in 1970 at the Mohave generating station located in South Nevada. The incident occurred due to the interaction of the turbine generator of a coal power plant with series compensated transmission lines and resulted in critical damages to the mechanical shaft of the turbine generator [14,15]. In 1977, the first sub synchronous torsional vibration event due to the interaction of HVDC controls with a turbine generator was reported in Square Butte in North Dakota [15]. The research conducted in [16] demonstrates that the interaction of the voltage control loop of static var compensators (SVC) at lower short circuit ratios could cause SSO. Hence, it is not a novel phenomenon associated only with IBRs. However, the SSO associated with IBRs is more complex and can cause power system instabilities, leading to severe damage to electrical equipment and mechanical facilities. Several destructive incidents have been reported in USA and China recently [15]. These recent events in the renewable rich grid calls for the immediate need of a real-time monitoring tool to observe the occurrence of harmful SSO and appropriate techniques to suppress them in due time to avoid the undesirable consequences of emerging types of SSO, such as damages to crowbar circuits, tripping of transmission facilities, and disconnection of generators from the network, etc.

Research is underway to develop dynamic SSO monitoring methods as well as cost effective and efficient techniques to suppress the emerging SSO in the renewable rich grid [14,17,18]. The focus of this study is to provide a comprehensive review of the existing SSO monitoring and damping techniques based on renewable energy systems, their limitations, and future research trends.

The rest of the paper is structured as follows. A brief review of the types of SSO is presented in Section 2 followed by a discussion of SSO in renewable energy systems in Section 3. Existing SSO monitoring methods and challenges associated with the existing methods are given in Sections 4 and 5, respectively. Existing SSO damping methods are given in Section 6. Challenges associated with the existing damping methods are given in Section 7. Finally, a discussion of future research trends and the conclusion are given in Section 8.

2. Sub Synchronous Oscillation Phenomenon

The definition of SSO according to the IEEE Sub Synchronous Resonance Working Group is as follows. "Sub synchronous oscillation is an electric power system condition where the electric network exchanges significant energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system following a disturbance from equilibrium" [13]. According to the classification of SSO by the IEEE Sub Synchronous Resonance Working Group, there are two types of SSO, namely sub synchronous resonance (SSR) and device dependent sub synchronous oscillation (DDSSO). Sub synchronous control interaction (SSCI) and sub synchronous torsional interaction (SSTI) are other types of SSO. However, they are not included in the formal classification. Figure 2 below shows an extended classification of SSO based on the formal classification by the IEEE Sub Synchronous Resonance Group and other types of SSO.

2.1. Sub Synchronous Resonance (SSR)

Sub synchronous resonance is defined as the "oscillatory attributes of electrical and mechanical variables associated with turbine generators when coupled to a series capacitor compensated transmission system where the oscillatory energy interchange is lightly damped, undamped or even negatively damped and growing" [13].

Series compensation is deployed in transmission lines to enhance the power transmission capability. The level of series compensation is the ratio of impedance of the series capacitor and the impedance of the transmission line. Generally, the level of series compensation ranges from 20–80% [14,19]. However, when the multi mass turbine generators are connected to series compensated lines, it will cause sustained or growing oscillations due to the exchange of energy between the electric network and the turbine generator at one or more natural frequencies of electrical and mechanical components of the combined system [13,14,20]. This condition is termed as SSR. Self-excitation and torque amplification are the two aspects of SSR.

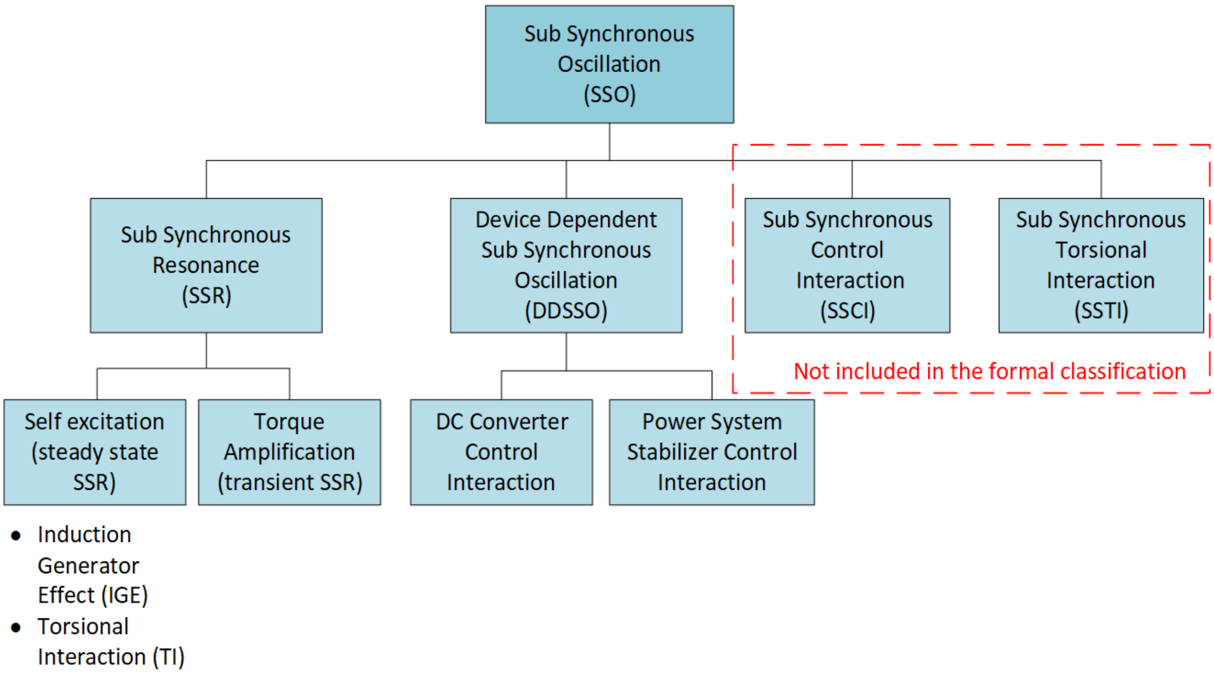

Figure 2. Extended classification of sub synchronous oscillation.

2.1.1. Self Excitation

Self-excitation is caused when the sub synchronous armature currents are sustained or enhanced by the sub synchronous armature voltage components, resulting from the induced sub synchronous rotor currents [13]. It is also referred to as steady state SSR.

Induction generator effect (IGE) is a form of self-excitation which occurs when the negative resistance to the sub synchronous current as viewed from the armature terminal exceeds the sum of armature and network resistance. It is a purely electrical phenomenon [13,20]. IGE occurs mostly in power systems with a higher level of series compensation [21]. Torsional interaction (TI) is the second type of self-excitation and involves electrical and mechanical dynamics of the system. When the equilibrium of the power system is disturbed, the turbine generator shaft system will oscillate at its torsional natural frequencies, thus inducing armature voltage components. If the induced sub synchronous armature voltage components are close to the electrical natural frequency of the system, a rotor torque will be produced. Self-excitation occurs if the sub synchronous torque component in phase with the rotor velocity deviation is equal to or exceeds the inherent damping torque of the rotating system. This is termed as torsional interaction [13,20]. TI occurs when the ratio of inertia between the turbine and generator are equal. The occurrence of TI in hydro power plants is less, as the generator inertia is much higher than that of hydro turbines. TI in wind power plants is also rare, as the low shaft stiffness of the wind turbine drive train causes torsional modes with low frequency [14,22].

2.1.2. Torque Amplification (TA)

TA is also called transient SSR and can occur due to network faults or switching operations. If the frequency of the electromagnetic torque component induced due to the interaction of the armature magnetic field with the magnetic field of the rotor coincides with the natural frequencies of the generator shaft, large torques will be observed due to resonance of electrical and mechanical natural frequencies. This phenomenon is defined as TA [14]. TA may cause fatigue in turbine generator shafts [13].

2.2. Device Dependent Sub Synchronous Oscillation (DDSSO)

DDSSO is the type of SSO that occurs when the turbine generator torsional system interacts with other power system components, such as HVDC converter controls, power system stabilizers (PSS), static var compensator (SVC), variable speed drives, or high-speed governor controls. In other words, DDSSO may occur due to the interaction of torsional systems of the turbine generator with any power control device having a wide bandwidth or any device having rapid response to speed or power variations in the sub synchronous frequency range [13,20]. DC converter control interaction and power system stabilizer control interaction are the sub classes of DDSSO. DC converter control interaction is caused by the interaction between the speed voltage component of the turbine generator and the firing angle of the of DC converter. Power system stabilizer control interaction occurs due to the voltage modulation of the generator field when there is a significant component of the generator speed in phase with the generator and exciter torque [13].

2.3. Sub Synchronous Control Interaction (SSCI)

SSCI is a new type of device dependent SSO caused by the interaction of a series compensated transmission system with a power electronic device. SSCI is differentiated from SSR, by the fact that it involves only electrical and control interactions and does not involve any mechanical interactions [23]. Although some researchers question whether IGE and SSCI are the same phenomenon, it is worthy to note that SSCI occurs only in asynchronous machines whereas IGE occurs in synchronous and asynchronous machines both [14]. Furthermore, SSCI occurs quicker in comparison to SSR, as it depends on the power electronic controller algorithm and may also grow faster due to the undamped oscillations being involved only with electrical and control interactions and not on mechanical components [14,21,23]. While SSR and SSTI depend on fixed torsional modes of the turbine generator, SSCI does not depend on a fixed frequency [23].

2.4. Sub Synchronous Torsional Interaction (SSTI)

SSTI is a device dependent SSO which occurs when the mechanical masses of a generator interact with power electronic devices, such as HVDC link, FACTS devices, PSS, or other power electronic devices [14,21,23]. SSTI should not be confused with TI. SSTI is different than SSR because the interactions which occur between the generator and power electronic device during SSTI does not involve resonance [14,24]. SVC and HVDC converters are the most vulnerable power electronic devices to SSTI [21]. Risk of SSTI in wind turbine generators is very low. This is because the low shaft stiffness coefficient only leads to low torsional natural frequencies [24,25].

SSO could be triggered by the interaction of various devices with the power network. Potential occurrence of SSO in different devices is summarized in Table 1 below. Figure 3 below indicates the grid interfacing configuration of each WTG type.

Table 1. Vulnerability of occurrence of SSO in different devices.

Device Type	SSR-IGE	SSR-TI	SSTI	SSCI
Synchronous generator	✓	✓	✓	✗
WTG type 1	✓	✓	✗	✗
WTG type 2	✓	✗	✗	✗
WTG type 3	✓	✓	✗	✓
WTG type 4	✗	✗	✗	✓
HVDC	✗	✗	✓	✗
SVC	✗	✗	✓	✓

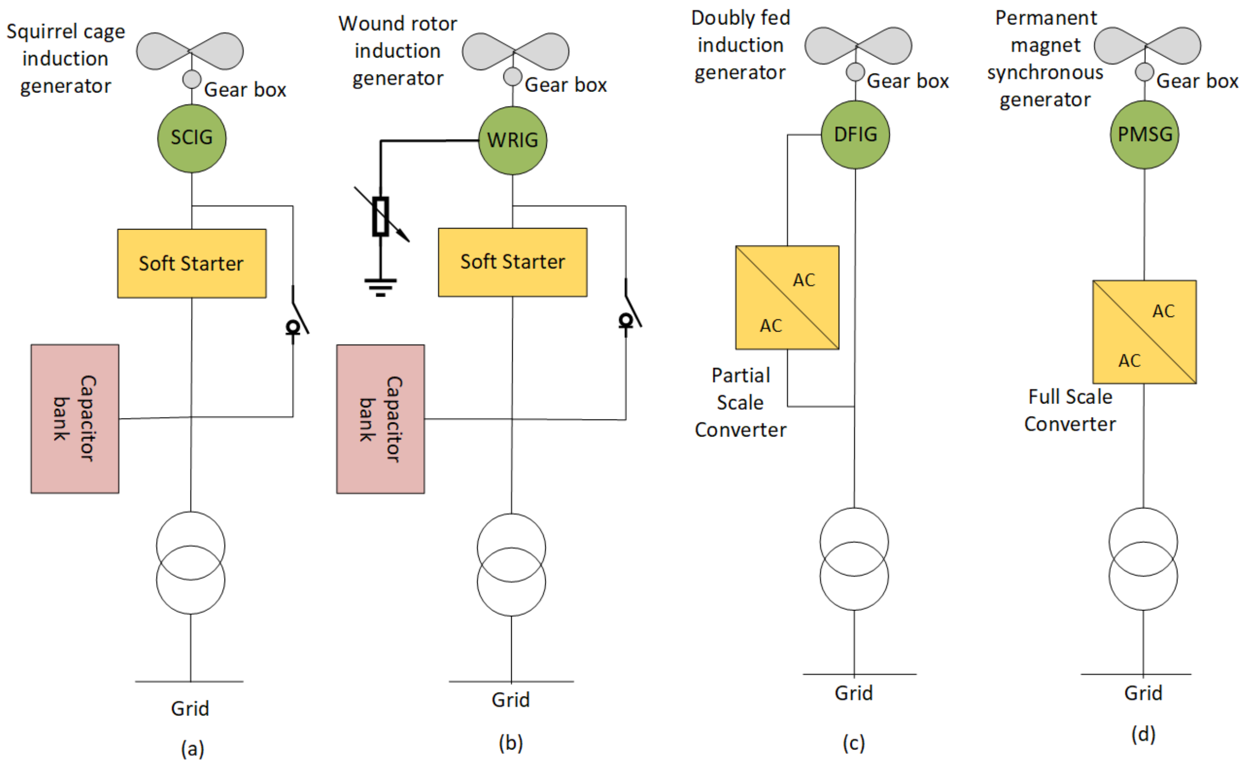

Figure 3. Grid interfacing configurations of WTGs (**a**) Type 1, (**b**) Type 2, (**c**) Type 3, and (**d**) Type 4.

3. SSO in Renewable Energy Systems

3.1. SSO in Wind Power Plants

Power generation using wind energy has become a popular form of renewable energy penetration of the power grid. The power transfer capability of existing transmission lines must be increased to accommodate the deployment of large-scale wind farms. This can be done by the addition of series compensation. However, the series capacitors pose a threat to the power system stability as it may cause sub synchronous oscillations in wind turbine generators (WTG). Type 1, Type 2, Type 3, and Type 4 are the four types of WTGs used in grid connected wind power plants. All types of WTGs are vulnerable to SSO [14]. The factors affecting SSO in each type of WTG will be discussed in this section. Table 2 summarizes the possible causes of SSO based on WTG type.

Table 2. Causes of SSO in different types of WTGs.

Type of WTG	Risk/Possible Causes of SSO	Refs.
Type 1	• SSO may occur in the form of IGE or TI when connected to the network via a series compensated line. • Grid interfacing configuration does not involve wind turbine controllers. Hence, no risk of SSCI. • There is no risk of SSR or no interaction with the torsional system and rectifier station current regulator when type 1 WTG is connected to the line commutated converter (LCC) HVDC transmission system with a series compensated line. However, there may be SSR instability if the wind farm is exposed to an AC line with a series compensation level greater than the critical level of compensation.	[26–28]
Type 2	• No risk of SSCI as it does not use power electronic converters for grid connection. • Capable of damping SSR occurring in series compensated lines.	[26,29,30]

Table 2. *Cont.*

Type of WTG	Risk/Possible Causes of SSO	Refs.
Type 3(DFIG)	• Most vulnerable to SSO. • SSO occurs due to the interaction of WTCs with series or shunt compensated lines, HVDC converters, FACTS controllers, filter circuits, or weak AC grid. • SSO can occur in the form of IGE, TI, and SSCI. • Wind speed and the level of series compensation are the factors affecting SSO occurring due to IGE. • SSCI in Type 3 WTG is affected by the rotor side converter (RSC) control parameters and grid side converter (GSC) control parameters. Impact of RSC is much stronger in comparison to GSC. • The number of doubly fed induction generator (DFIG) wind turbines in service has a nonlinear impact on system damping following the SSR phenomenon.	[14,23,25,26,31,32]
Type 4(PMSG)	• SSO occurs due to the interaction of the Type 4 WTGs GSC controller and weak AC grid. • Frequency and stability of the SSO depends on short circuit ratio (SCR), capacity of wind turbines in operation, parameters of WTG converters, and control strategies. • Can cause sub and super synchronous oscillations due to the interaction of GSC controllers and series compensated transmission lines at a high level of compensation. • No risk of direct torsional interaction as the full-scale converter isolates the wind turbine from the resonances occurring in the series compensated network.	[26,33–39]

3.2. SSO in Solar PV

The topology of solar PV and Type 4 (PMSG-based) wind turbines is similar, as both utilize full power voltage source converters (VSC). Although the rated capacities of VSCs are different in the two cases, the DC-AC control mechanism and modulation techniques are similar. Hence, they depict similar characteristics when observed from the perspective of the AC grid [40,41]. PV plants and Type 4 WTGs are comparatively immune to SSR than Type 1, 2, and 3 WTGs since they are decoupled from the electric source [42]. However, there is an underlying risk of occurrence of SSCI in grid connected PV systems [43]. Very limited research has been conducted on the occurrence of SSO in grid connected PV plants. SSO in PV plants connected to weak AC networks has been studied in [40]. It shows that resonance could occur at instances when the impedance of the grid connected PV system becomes capacitive in the sub synchronous frequency domain. Further, the eigenvalue analysis conducted in [41] shows that the voltage outer loop controller parameters in a grid connected PV system strongly affect the SSO conditions. It is shown that the current inner loop controller also has an impact on the SSO conditions, although the effect is lesser in comparison.

3.3. SSO in Hydro Power Plant

The risk of occurrence of SSO due to torsional interactions is low in hydro power plants as the inertia of the generator is much higher than the turbine inertia. Although SSO in hydro power is not explored due to the above reason, there is a possible risk of SSO in modern hydro plants employing the doubly fed induction machine (DFIM) with PEC for variable speed operation [14,44].

3.4. SSO in Other Renewable Energy Sources

There are no reported SSO incidents in other renewable energy sources, such as tidal energy, geothermal energy, or biomass energy. However, there could be a possible risk of SSO based on the adapted technologies. For instance, SSO could occur in tidal turbine generators. The power generation process by tidal stream is similar to wind power generation by air currents. Furthermore, tidal turbine generators are either the squirrel cage induction generator (SCIG), doubly fed induction generator (DFIG), or permanent magnet synchronous generator (PMSG) [45]. Hence, there is a potential risk of SSO due to interaction of tidal turbine generator converter control with components of the power grid. Risk of SSO in geothermal energy or biomass energy-based generation systems has not been discussed in the literature.

4. Existing SSO Monitoring Techniques

Although ample research has been done on the causes of SSO, there is a pressing need for the development of real-time SSO monitoring techniques to identify possible threats and activate appropriate mitigation measures to ensure the safety and reliability of the power system. Identification of SSO parameters is a key factor in the process, and many SSO parameter identification techniques are presented in the literature.

Existing oscillation identification techniques can be classified under three groups: time domain, frequency domain, and time-frequency domain methods. Prony [46] estimation of signal parameters via the rotational invariance technique (ESPRIT) [47] and particle swarm optimization [48] are time domain methods and use instantaneous voltage and current measurements. However, these methods require details of the system model to determine the parameters. Hilbert Huang transform [49] and variational modal decomposition (VMD) [50] are time-frequency domain methods and can be used to obtain parameters of all oscillation modes although it requires extensive computations. Frequency domain methods are based on Discrete Fourier Transform (DFT) [51] and give accurate results with improved DFT algorithms. However, spectrum leakage, spectrum aliasing, and fence effect are the main issues related to DFT. Therefore, as an alternative to overcome the above issues, artificial intelligence (AI) has been recently used for power system oscillation identification by feature extraction of historical data [52]. The SSO monitoring techniques presented in the literature can be discussed under the following three sections.

4.1. SSO Parameter Estimation-Based Techniques

The SSO parameter estimation-based techniques identifies the occurrence of SSO by using algorithms that determine the SSO parameters. The algorithms are designed to estimate parameters, such as frequency, amplitude, and damping. Hence, the severity of the oscillations can be determined, and the mitigation measures can be activated accordingly. Few such methods are discussed in Table 3 below.

Table 3. SSO parameter estimation techniques.

Technique	Estimated Parameters	Features	Limitations	Refs.
Four-point interpolated DFT for rectangular windowed phasor and DFT spectral analysis of Hann windowed phasor	Frequency, amplitude, and damping factor of SSO	Can be used even if the system is off-nominal, dynamic, or noisy.	Application of the method is questionable when the off-nominal condition is severe and the SSO frequency is high.	[53]
DFT spectral analysis and correction of spectral analysis by construction of a waveform proportional to the spectrum of amplitudes of the measured synchro phasor	Frequency and amplitude of fundamental and SSO	Can accurately obtain fundamental and SSO parameters using synchro phasor measurements.	• Time consuming. • Does not consider the damping factor of SSO. • Accuracy in dynamic conditions is uncertain.	[54]
DFT spectral analysis	SSO frequency	Easier to implement.	Does not consider the effect of power electronic-based devices on the level of sub synchronous variations.	[55]

Table 3. *Cont.*

Technique	Estimated Parameters	Features	Limitations	Refs.
Hann windowed three-point interpolated DFT	Frequency, amplitude, damping, and phase of SSO	• High accuracy under off-nominal, dynamic, and noisy conditions. • Can identify SSO parameters accurately by suppressing the errors caused by spectrum leakage and fence effect. • Less computational complexity.	If synchro phasor calculation methods other than DFT are used by PMU suppliers, the windowed synchro phasor model under SSO is different.	[56]
Sub and super synchronous harmonic detection based on DFT	Frequency, amplitude, and phase of sub and super synchronous oscillations	• Can detect both sub and super synchronous phasors with high precision. • Not affected by random noises and higher order harmonics.	Requires data of instantaneous signals, PMU data are insufficient.	[57]
Multi-synchro squeezing transform (MSST) and least squares estimation	Frequency, amplitude, damping, and phase of SSO	• Does not require prior knowledge about the oscillations unlike other model-based methods such as Prony. • Less computational burden and strong anti-noise ability making it suitable for online applications.	Possible data loss in PMU measurements must be addressed separately.	[58]

4.2. Techniques Based on Sub Synchronous State Estimation (SSE)

Sub synchronous state estimation is another category of SSO monitoring techniques. State estimation (SE) in general is used to obtain the most accurate estimate of the system state using mathematical modeling. Its primary objective is to reduce the possible errors and inconsistencies in phasor measurement unit (PMU) data and provide reliable state estimates such that it can be used for dynamic monitoring and control the power grid [59,60]. Sub synchronous state estimation is similar to conventional SE. However, frequency measurements obtained at different locations may vary unlike in the conventional SE method. Therefore, the common sub synchronous frequency must be determined prior to the estimation of the state vector [61]. SSE can therefore be used to monitor SSO in the power grid as the method provides a global view of SSO as well as the source/path of the oscillation. However, limited research has been done in this context.

Wide area monitoring and the early warning system for SSO presented in [61] uses SSE to observe the SSO dynamics and determine the stability of SSO using oscillation damping based on the least square estimation algorithm and by the analysis of frequency characteristics using an aggregated impedance model. Depending on the pre-determined stability criteria, if harmful SSO is detected, an alarm will be sent such that relevant actions could be initiated to mitigate the adverse effects of SSO. This method can overcome the issue of the inability of the existing PMUs to capture inter harmonics accurately as it uses locally deployed sub synchronous phasor measurement units (S-PMUs) to capture data. Although time delays due to data processing and communication is possible, the time delays are low and do not have a significant impact on real-time monitoring of the system.

4.3. Artificial Intelligence (AI)-Based Techniques

The use of AI-based techniques for SSO monitoring is an emerging area of research. Since SSO does not always occur, performing the above mentioned SSO parameter identification techniques on each PMU data will be time consuming and unnecessary. The applicability of parameter identification methods for real-time oscillation monitoring is therefore impractical. AI-based techniques have been proposed and validated in the recent past as a possible solution to the above drawback. Some of the methods are given below.

The data driven SSO identification method introduced in [52] detects SSO from a large set of PMU data. Accordingly, the multiple support vector machine (SVM) algorithm is used to detect SSO. Appropriate SSO parameter identification techniques can then be used to estimate SSO parameters. The advantage of this method is that it can detect SSO from a vast set of PMU data, and relatively low computations are required as SSO parameter identification needs to be carried out only in the selected data. Therefore, this method can be used for real-time monitoring of SSO in the power grid.

Another technique for SSO online monitoring and automatic alarming is presented in [62], where Fast Fourier Transform (FFT) is applied to the PMU current phasor to obtain sub synchronous frequency components. Harmful SSO components are then detected by a trained SVM algorithm, and finally, a threshold determined by frequency susceptibility, amplitude attenuation, and energy accumulation is used to decide whether to transmit an alarm signal.

The decision Tree (DT)-based SSO identification and alarming method in [63] uses historical PMU data to identify the SSO threshold using a DT algorithm where the threshold depends on the functional relation between the extracted feature vector and the label, and the threshold can be adjusted by changing the labeling criteria to suit the requirement. Once the threshold is identified using PMU data offline, online SSO detection can be carried out. For suspected SSO, FFT analysis is performed to calculate the amplitudes and frequency. If the frequency of suspected SSO is closer to the torsional vibration frequency of the generator shaft, the amplitude is large or persist for a longer duration, an alarm signal will be sent.

The research work [52,62,63] shows a similarity. Hence, their basic process can be recapped as shown in Figure 4. Further, a comparison of the above research work with respect to the basic steps is given in Table 4. Current phasor amplitude data obtained by PMU measurements is used for feature extraction in all three methods given above.

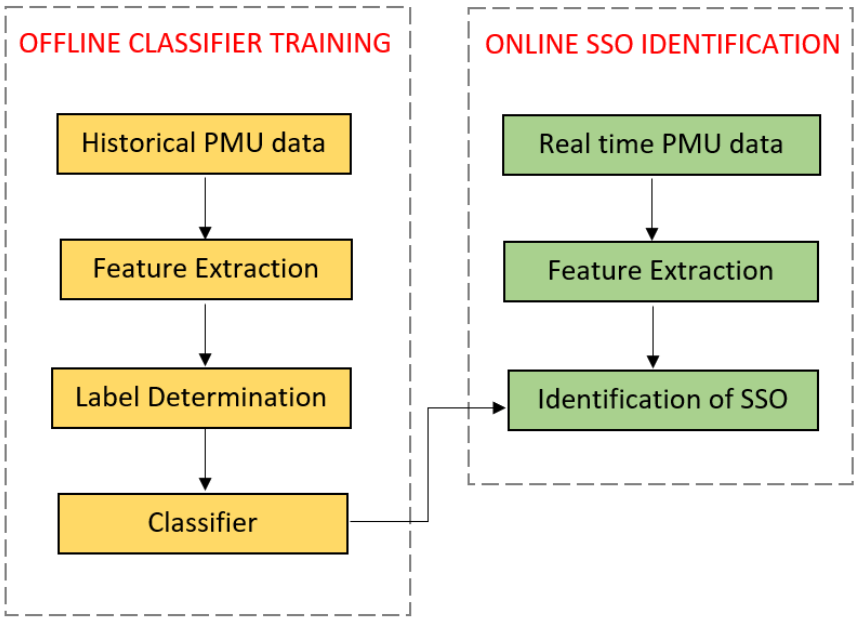

Figure 4. General process of SSO identification in research work.

Table 4. Comparison of basic steps of AI-based methods.

Feature Extraction	Label Determination	Type of Classifier	Additional Features	Limitations	Refs.
• Trend • Envelope volatility index • Length of stationary subsequence	Using FFT spectral analysis	Multi-SVM classifier	• Update of SVM classifier via incremental learning. • Performing correction of classification result to reduce misclassifications.	Inability of existing PMUs to capture SSO accurately is not rectified before using PMU data to train the model.	[52]
Amplitude percentage	Based on parameters K, M, and N determined according to the amplitude percentage distribution	SVM classifier	Adaptive duration threshold for alarming of SSO.	• Feature vector samples are labeled based on parameters determined by the analysis of a large PMU dataset obtained from the China power grid. Hence, the applicability of the model in a different location, under different SSO types, is unknown. • Reporting rates of the PMUs used to obtain datasets for training is 100 Hz. Hence, super synchronous oscillations are not captured.	[62]
Amplitude of fluctuation	Parameters K, M based on amplitude and saliency respectively	DT classifier	Has analyzed the adjustment of labeling criteria to suit the actual conditions.	• Training data is labeled using two parameters M and K based on large amplitude and saliency. The initial values for M and K must be adjusted if the labeling criteria does not suit actual conditions. Therefore, model training becomes more time consuming. • Inability to capture super synchronous oscillations as the reporting rates of the PMUs used to obtain datasets for training is 100 Hz.	[63]

It is worthy to note that the existing methods are based on deterministic machine learning (ML) algorithms, such as SVM and DT. The DT algorithm has less computations although it could be subjected to overfitting [52]. SVM on the other hand is a more robust algorithm. Classification of data is done by finding the optimal hyperplane with a considerable margin [64]. However, deterministic ML algorithms do not reflect any idea regarding the uncertainty involved with the prediction. The use of probabilistic ML algorithms is therefore a better choice for decision making as it gives information regarding the level of confidence of the predicted outcome.

5. Challenges Associated with Existing SSO Monitoring Techniques

SSO must be monitored using appropriate techniques to identify their severity. If the severity is high, suitable protection mechanisms can be activated. However, more research must be dedicated to address the limitations of the available techniques. Based on the review of existing SSO monitoring methods, the following challenges can be identified:

- Most of the SSO monitoring methods discussed in Section 4 above use measurements obtained by PMUs. Phasor measurement units provide information regarding current and voltage phasors, frequency, and rate of change of frequency using phasor estimation algorithms. Furthermore, PMUs scattered at different locations can transmit data to the phasor data concentrator (PDC) in a span of approximately 1 µs, enabling efficient and reliable real-time monitoring of power system dynamics [65,66]. However, the following key issues associated with synchro phasor technology poses limitations on SSO detection using PMU measurements:
    - Available PMU technology is designed only to extract the fundamental component of the signals. The increased use of renewable energy sources and addition of power electronic devices to the grid have introduced a large number of inter harmonics that are non-integer multiples of the fundamental signal, thus changing the measurement of the fundamental component.
    - Furthermore, one sub synchronous oscillation frequency component could be caused by two harmonics, resulting in aliasing [67]. Therefore, appropriate techniques must be employed to address the above issues and enhance the performance of PMUs before using PMU measurements for SSO detection.
- The maximum available reporting rates of PMUs installed at present are limited to 100 Hz/120 Hz. If the SSO frequency is above half of the reporting frequency, the corresponding frequency cannot be restored according to the Nyquist Shannon sampling theorem [68]; hence, the SSO cannot be monitored accurately. In case the reporting rate of the installed PMUs is 50 Hz/60 Hz, the frequencies above 25 Hz and 30 Hz, respectively, cannot be observed.
- Although PMU measurements are commonly used for the available SSO monitoring techniques, certain algorithms, such as the sub/super synchronous algorithm proposed in [57], require the use of instantaneous signals for SSO identification as PMU data are insufficient. In such cases, data from fault recorders must be used. However, acquiring data from fault recorders will be difficult and time consuming as they are placed in local stations individually. Furthermore, direct comparisons cannot be made among the non-time synchronized data obtained from fault recorders at different locations [54].
- The computational burden of noise filtering processes of standard SSO identification algorithms can be stated as another challenge associated with existing techniques [52]. Hence, advancements must be made to eliminate the noise component from signals used for SSO identification.

6. Existing SSO Mitigation Methods

Sub synchronous oscillations affect the reliability of the power grid as severe consequences may occur if they are not suppressed in due time. Recently reported sub synchronous oscillation events highlight the requirement of efficient mechanisms to alleviate the emerging SSO conditions due to the deployment of large-scale wind farms and grid connected solar PV plants. Existing techniques for SSO damping are discussed below.

6.1. FACTS Devices

The modification of FACTS devices has been identified as an efficient way of alleviating SSO conditions although it is not the primary role of FACTS devices. The literature reveals that different types of FACTS devices have been modified to achieve successful damping of SSO. Table 5 gives an overview of the existing SSO mitigation techniques based on FACTS devices.

Table 5. SSO damping methods based on FACTS devices.

Device	Technique/Features	Advantages	Refs.
Static var compensator (SVC)	SVC augmented with a damping controller installed at the induction generator terminal and uses generator speed deviation as the input signal.	Damping of self-excited SSO and torsional oscillations can be significantly improved.	[69]
	SVC with a damping controller is installed at the point of common coupling (PCC) and line current is used as the feedback signal.	Communication delay associated with remote signals can be avoided as it uses a local feedback signal.	[70]
	SVC-based damping controller where the controller gain is adaptive to the level of wind generation.	Suitable for damping of SSO for a range of wind generation levels and effective as the wind generation levels varies under practical conditions.	[71]
	Adaptive Neuro-Fuzzy Interference Systems (ANFIS) controller is used as an auxiliary controller for SVC.	Can damp SSO under nonlinear system behavior of the power system.	[72,73]
Thyristor controlled series capacitor (TCSC)	Constant current controller used for closed loop current control of a TCSC.	SSO due to IGE and torsional interaction can be damped effectively even during a severe fault.	[74]
	TCSC with auxiliary fuzzy logic damping controller (FLDC).	Pitch angle of the wind turbine can be controlled to an optimal level during times of high wind speed using the FLDC controls.	[75]
	Adaptive neurocontroller is designed to generate a control signal to adjust the firing angle of the TCSC such that the SSO can be damped out.	Since this is an AI-based technique, accurate system modeling is not required. Therefore, this method is well suited for applications involving nonlinear systems.	[76]
Gate controlled series capacitor (GCSC)	SSR damping controller is designed for the GCSC using the root locus method. The input signal to the damping controller is the line current, which is a local signal.	Successful damping of SSR mode when line current is used as the input signal. However, it should be noted that the stability of the super synchronous mode is reduced.	[77]
	Residue-based analysis is conducted to select a suitable input signal such that the stability of both SSR and super synchronous modes can be increased.	A comparison among the three input signals rotor speed, line current, and voltage across series capacitor indicate that the optimum signal to be used as the input for the damping controller is the voltage across the series capacitor.	[78,79]
	Impedance controlled GCSC design for fixed speed wind turbine generator systems. It uses a proportional-integral (PI) regulator to control the impedance of the GCSC, which in turn enables power flow control of the transmission line.	Successful in mitigating SSR due to IGE and TI in wind farms even at higher series compensation levels.	[80]
Sub synchronous series compensator (SSSC)	SSSC augmented with an auxiliary damping controller where the damping controller is designed with two control loops based on rotor speed deviation and active power variation in a specific time interval.	SSSC with the damping controller shows a significant improvement in the transient stability margin compared to the same damping controller with a STATCOM.	[81]
	SSSC-based damping control strategy for a PMSG-based wind farm where the sub synchronous components during SSO will be extracted from the voltage at the point of common coupling (PCC) and incorporated into the original voltage control signal.	Can damp SSO in a PMSG-based wind farm successfully.	[82]
Static compensator (STATCOM)	Firing angle of the inverter is controlled using a PI controller to modulate the exchange of reactive power between the STATCOM and the AC system, thereby stabilizing torsional SSR occurring in wind energy systems. PI parameters are tuned using the Nelder and Mead optimization method.	A simpler controller design, hence, requires less hardware for implementation. The Nelder and Mead method for parameter tuning ensures robustness in the selected PI parameters.	[83]
	Controls the angular difference between the STATCOM terminal voltage and the bus voltage at the PCC using output current of the reactive component of the STATCOM as the feedback signal.	Can suppress transient SSR occurring due to network faults. This method demonstrates a substantial reduction in shaft torque. Hence, the occurrence of cyclic fatigue can be avoided by using this STATCOM controller.	[84,85]
	STATCOM controller based on the control of both modulation index and phase angle.	Modulation index can control electrical modes effectively. It is also observed that the modulation index is more effective compared to the phase angle difference when the size of the wind farm is increased. This method can be used to mitigate SSR in both steady state and transient state.	[86]
Unified power flow controller (UPFC)	Two sub synchronous damping control loops are added to the series and shunt branches of the UPFC.	Better damping of SSO can be achieved since damping controllers are embedded to both series and shunt branches of the UPFC.	[87]
	The ANFIS controller added to the shunt controller of the UPFC along with a fuzzy logic damping controller for optimal control of the pitch angle of the wind turbine during higher wind speed.	Mechanical and electrical power has been maintained in the same range by the optimal pitch angle control using the FLDC.	[88]

6.2. Converter Control of Distributed Energy Resources (DER)

Although FACTS devices can be used to damp SSR effectively, it is not economical to use FACTS devices just for the purpose of SSR mitigation due to the high cost involved.

The modification of converter controls is a cost-effective alternative. Existing SSR damping methods based on the modification of converter controllers of distributed energy resources is discussed below.

6.2.1. Wind Farm-Based Converter Controls

Power generation from wind energy has increased substantially over the past decade. WTGs of Type 3 and Type 4 are the most deployed configurations in large scale wind farms. Type 3 DFIG-based WTG is composed of the grid side converter (GSC) control and rotor side converter (RSC) control as shown in Figure 5. The primary task of the GSC loop is to maintain the stator terminal voltage and DC link voltage at constant levels, whereas the RSC control loop regulates the stator reactive power and electrical torque [89].

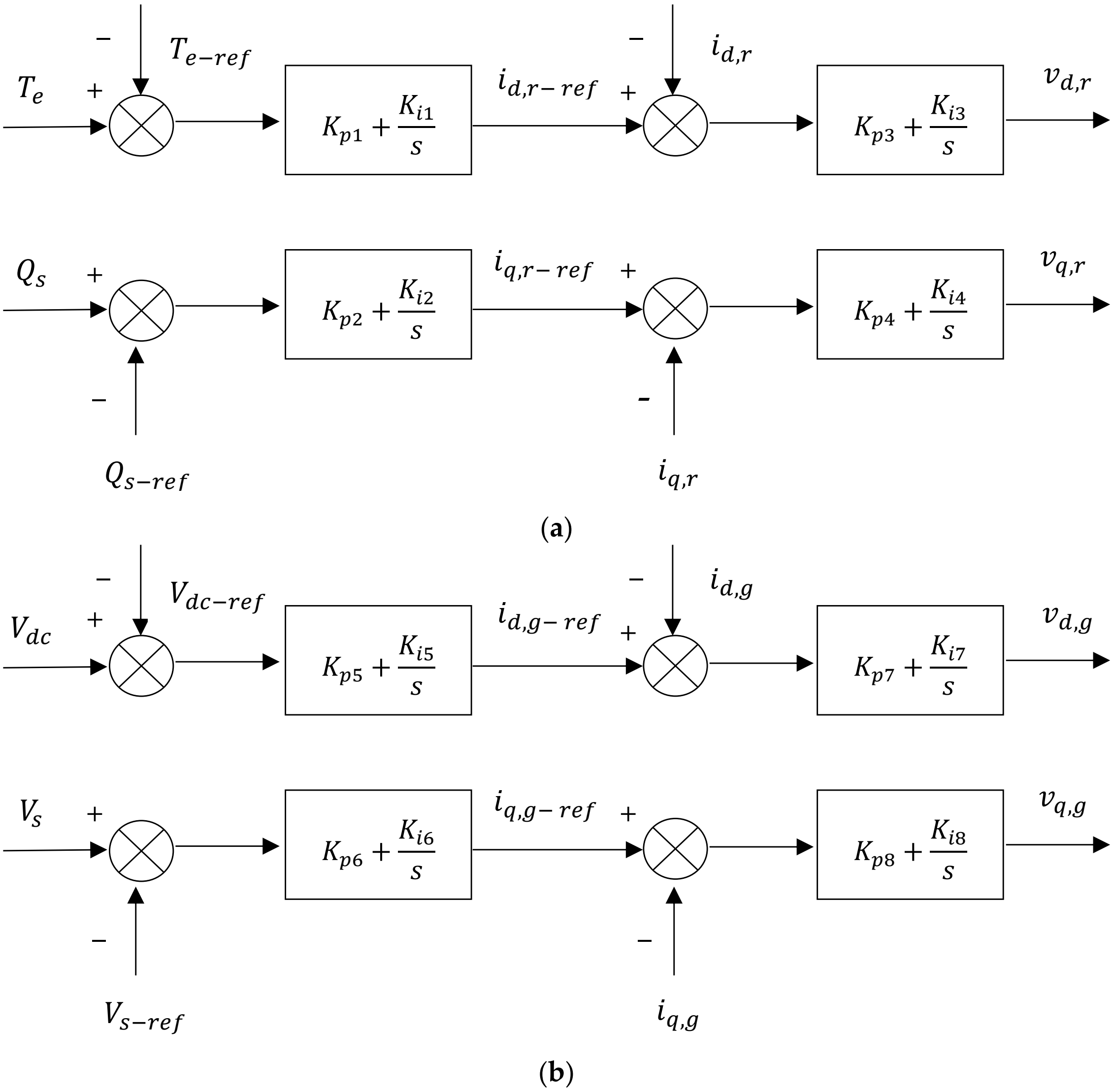

Figure 5. DFIG converter control system: (**a**) RSC control, (**b**) GSC control.

The GSC and RSC control loops of the DFIG WTG can be modified to mitigate SSR conditions. Table 6 summarizes the existing SSO damping techniques based on the modification of the above controllers. Furthermore, the RSC current controller loop has a stronger impact on the mitigation of SSR compared to the GSC controller [14]. The comparison of a supplementary damping controller added to RSC and GSC demonstrates that the RSC damping controller shows more damping and robustness to variations in operating conditions [90].

Table 6. Wind farm-based converter controls for SSR damping.

Type of Modification	Technique	Advantages	Refs.
Augmentation of the stator voltage control loop of the GSC	Damping controller using rotor angular speed as the input signal.	Can damp SSR successfully.	[91]
	Multi-channel damping controller with modal speeds as inputs. Gain and phase compensation are performed on each input.	Ability to damp each oscillation mode.	[92]
	Fuzzy logic damping controller having rotor speed deviation as the input signal.	Can accommodate nonlinear system behavior under disturbance conditions. Hence, can be used over a range of operating conditions.	[93]
	Damping controller designed using observed state feedback control.	Any local signal can be used as the input signal. Therefore, communication delay associated with input signals obtained using WAMS could be overcome by considering a local signal.	[94]
	A nonlinear damping controller is designed using the feedback linearization technique and sliding mode control.	Can damp SSCI successfully and maintain the stability of the system under varying operating conditions.	[95]
Addition of supplementary controllers on the q-axis inner controller of the GSC	Power system stabilizer designed using a probabilistic approach. DC link voltage deviation is used as the input signal.	Successful damping of SSCI over a range of operating conditions.	[96]
	Proportional feedback controller using electrical power as the feedback signal.	Simpler controller structure.	[97]
	Nonlinear controller based on the partial feedback linearization (PFL) technique.	Can successfully damp SSCI under varying atmospheric conditions as complete system dynamics are not required to be modeled when the PFL technique is used.	[98,99]
Modifications of RSC controller	A novel two degree of freedom control mechanism is used for the design of the damping controller added to the RSC current control loop.	Can suppress SSR due to IGE successfully.	[100]
	Nonlinear damping controller based on PFL. It controls the current flow in the RSC to produce damping torque sufficient to damp critical torsional frequencies.	Can address the uncertainties associated with practical wind generation and able to sustain fault ride through operation of DFIG wind farm during severe contingencies.	[101]
	A nonlinear sliding mode control (SMC)-based technique to eliminate the dynamics of the rotor circuit causing SSR. In this method, SMC is used to collapse the rotor dynamics by limiting the current flow to predefined values of reference currents.	A comparison of the method with the PFL technique in [101] shows that this method demonstrates consistent performance unlike the PFL-based controller of which the performance is affected at higher levels of series compensation.	[102]
	H_∞ damping controller using a multi-input multi output (MIMO) uncertain state space model.	Satisfactory SSCI damping during lower wind speeds, higher level of series compensation, and uncertain grid parameters.	[103]
	Installation of a sub synchronous suppression filter at the d-axis inner current loop of the RSC.	Easier implementation and robustness to varying operating conditions.	[104]
	Installation of notch filters at d-axis and q-axis of the RSC controller.	Implementation is easy and does not affect the DFIG dynamics.	[105]

6.2.2. Solar PV-Based Converter Controls

There has been a significant increase in the penetration of large-scale grid connected photovoltaic (PV) plants recently. Although the addition of PV farms increases the risk of occurrence of SSR, modifications can be made by the addition of supplementary controllers for the damping of SSR. Table 7 summarizes the existing PV-based damping methods.

Table 7. SSO damping using PV farms.

Technique	Advantages	Limitations	Refs.
PV-STATCOM	• As per transmission grid code requirements, solar farms should shut down during large voltage deviations. This method allows the solar farms to return to energy production within a period of less than 10 s rather than shutting down during large voltage deviations due to SSR. • Cheaper solution than a conventional STATCOM. • Economic and feasible solution for SSR mitigation when generator based SSR damping devices are inadequate or not considered.	• Applicable only if connected close to the terminals of the synchronous generator. • Load frequency issues, which occur following the disconnection of the solar farm, are not considered in the scope. • Grid codes should be revised to accommodate smart inverter functions.	[5]
Adding an auxiliary damping controller to the main control loop of the PV plant.	Increased PV penetration can be used as an effective alternative to enhance power system stability and control.	The controller fails to damp SSR when the time delay associated with the WAMS signal is taken into consideration.	[17]
GSC control of the PV farm is augmented with a damping controller which uses the voltage across the series capacitor as the input for the damping controller.	Voltage across the series capacitor is used as the input for the damping controller since rotor speed of the generator may not be effective when parallelly connected turbine generators are used.	Based on the assumption that there is no delay as the series capacitor voltage is monitored continuously.	[42]

6.2.3. Battery Energy Storage System-Based Converter Controls

With the development of IBR technologies, there has been a widespread use of battery energy storage systems (BESS) in smart grids recently. A method to obviate SSR using BESS has been proposed in [18] where a supplementary damping controller is designed for the active power control loop of the BESS. This method uses PMU data to obtain the input signal of the damping controller. The effectiveness of the proposed controller is demonstrated with up to 5 milliseconds of communication delay of WAMS signals.

6.3. Other SSO Damping Methods

In addition to FACTS-based damping controllers and the modification of converter controls, several other methods have also been reported in the literature. Some of them can be applied during network planning and design while the others involve modifications of the existing system components. Several methods are discussed below.

A. Special purpose shunt voltage source converter (VSC)

Due to the cost considerations, use of FACTS devices for SSO damping is limited to instances when it is already installed in the network. Using shunt-VSC with well-tuned filters that could extract sub synchronous frequencies has been proposed as an economically feasible alternative [89]. A shunt VSC along with a properly designed controller could dissipate the resonance power resulting from SSCI by absorbing the sub synchronous currents, thus damping out the SSCI [106]. A robust SSR damping control strategy is proposed in [107] where the sub harmonic voltage source converter (SVSC) injects sub synchronous currents to stabilize SSR. The parameters of the damping control strategy are tuned using the genetic algorithm and simulated annealing algorithm (GASA).

B. Proper control of series capacitor

Series compensation is a popular and effective means of increasing the power transfer capability of transmission lines although it increases the risk of SSO. A possible solution for this is proposed in [108] where a control algorithm is used to bypass the series capacitor when SSR is detected and reinsert when the risk of SSR is reduced. This method is cost effective as it can be implemented at no extra cost.

C. Sub synchronous frequency relay

Sub synchronous frequency relay acts as a protection mechanism to prevent damages to equipment such as crowbar circuits and series capacitors if SSR occurs. A microprocessor-based sub synchronous frequency relay is proposed in [109]. It contains a range of tripping frequencies allowing the grid operators to customize settings according to the requirement. Another technique to detect sub harmonic components using voltage and current detectors is proposed in [110]. The sub harmonic relay will calculate individual sub harmonic components as well as the total sub harmonic distortion factor and generate an alarm or isolate the system based on the calculated values and user defined threshold levels.

D. Power system design improvements

Factors such as the level of series compensation and grid strength show a direct impact on the SSR phenomenon. The net series compensation level of the power grid increases due to external faults. If it exceeds a certain level, SSR could occur. Therefore, the series compensation level should be kept at a permissible level when the power network is designed such that the increased series compensation levels due to faults do not trigger SSR [14].

It has been discussed in Section 3.1 that type 4 WTGs interact with weak AC grid causing SSR. Therefore, the risk of occurrence of SSR could be minimized if appropriate measures are taken to increase the strength of the power grid [89].

Although many SSO mitigation methods have been discussed in the literature, each technique has its own advantages and disadvantages. A summary of the existing mitigation methods with the advantages and limitations is given below in Table 8.

Table 8. Summary of advantages and limitations of the existing SSR mitigation techniques.

Device/Technique	Advantages	Limitations
FACTS devices • Variable impedance type FACTS controllers (SVC, TCSC, GCSC) • Voltage source converter-based FACTS controllers (SSSC, STATCOM, UPFC)	Can mitigate sub synchronous resonance effectively.	Installing FACTS devices just for SSR mitigation is not economical due to high cost involved. However, FACTS devices installed for reactive power compensation as per grid code requirements can be modified with additional controllers to mitigate SSR.
Special purpose shunt VSC	Economically viable alternative.	Difficulty in tracking the frequency variations of fundamental and sub synchronous components simultaneously.
Converter Controls	• Cheaper solution compared to FACTS devices. • Faster implementation. • Can avoid generator tripping.	• Applicable only to converter-based WTGs. • Some methods have not considered the time delay associated with WAMS signals.
Proper control of series capacitor	No extra cost as the method only involves bypassing the series capacitor upon detection of SSR.	Has a risk of triggering SSO during capacitor switching.
Sub synchronous frequency relay	Can detect sub synchronous frequencies that coincide with other power system frequencies.	Cannot be used to mitigate SSCI.
Power system design improvements, such as selection of proper series/shunt compensation levels	-	Shunt compensation leads to super synchronous resonance.

7. Challenges of the Existing Mitigation Methods

It is vital to suppress the SSO conditions in due time to ensure the stability of the power grid. Despite the many techniques proposed in the literature to mitigate the harmful SSO, there are challenges that must be addressed to develop efficient and practical mitigation strategies. The following challenges have been identified based on the above review:

- Although ample research has been done on the use of FACTS devices for the mitigation of SSR and are proven to be effective, it is not economical to use FACTS devices just for the purpose of SSR damping due to the high cost involved in installation and maintenance. Therefore, research is required to find more cost-effective solutions for the mitigation of SSO.
- The augmentation of converter controls is a cheaper alternative for SSO damping. However, most of the proposed SSO damping control strategies are based on the modification of GSC and RSC of type 3 (DFIG-based) WTGs. Limited research has been conducted so far based on the modification of type 4 WTGs and PV plants for SSO damping. Additionally, some of the proposed methods fail to damp SSO under practical scenarios. For instance, the damping controller in [17] cannot damp out the SSO successfully when the time delay associated with the WAMS signal used as the input signal to the damping controller is taken into consideration.
- Experimental validation of the proposed SSO damping methods has been conducted based on the model aggregation technique in simulation studies. However, a practical system could be comprised of different types of WTGs and controllers which cannot be considered during the simulations. Hence, the performance of the damping controllers may not be as satisfactory under actual conditions.
- Although special purpose shunt VSC is an economically feasible solution for the mitigation of SSO, the challenge in tracking the fundamental and sub/super synchronous components which keep varying during the oscillation incident pose limitations on the use of special purpose shunt VSC for SSO damping [89].

8. Conclusions and Future Work

This paper presents an overview of the types of SSO and the causes that initiate SSO in different types of renewable energy resources followed by a comprehensive review of the existing sub synchronous oscillation monitoring and damping techniques and their limitations. In conclusion, it must be noted that although the transition of the power grid from conventional energy sources to renewable energy brings out a more sustainable power network, the expected benefits could be achieved only if suitable measures are taken to ensure the reliability of the grid. Emerging types of SSO, such as SSTI and SSCI discussed in this paper, are some such issues to be addressed to assist a smoother transition towards a renewable rich grid. Existing monitoring and control mechanisms have not been capable of mitigating the recent SSO incidents that have taken place in USA and China. Complex dynamics associated with the recent technological developments must be accommodated in monitoring and control mechanisms to enhance the resilience of the grid. Despite the many research studies proposed thus far, only a few methods can be implemented practically due to various concerns. Hence, more research must be dedicated to address the challenges in the existing monitoring and damping methods to ensure the stability of the grid. Some research needs can be listed as follows:

- As PMUs are the widely used technology at present for dynamic monitoring of the power grid, measures should be taken to improve the accuracy of sub synchronous components reported by them. If not, the algorithms developed to identify SSO components will be meaningless. Hence, further research must be conducted to develop PMUs that can report sub synchronous frequencies accurately.
- Studies on the impact of noise on SSO identification and techniques to eliminate noise from the measurement signals is another area of research requiring attention.

- Use of Artificial Intelligence for SSO identification is an emerging area of research. As the SSO does not occur all the time, running algorithms to calculate SSO parameters of all PMU data will be unnecessary. Research is required to develop both deep learning (DL) and machine learning (ML) techniques for SSO identification.
- Further studies are required to develop cost effective SSO damping techniques based on the modifications of PV plant converter controls.
- A method to trace fundamental and sub/super synchronous components simultaneously is required such that effective SSO damping could be achieved.

Author Contributions: The authors contributed to this manuscript as follows: conceptualization, methodology and formal analysis were done by U.P. and R.Z.; writing—original draft preparation was done by U.P.; writing—review and editing was done by U.P., R.Z. and A.M.T.O.; supervision was done by R.Z. and A.M.T.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge Auckland University of Technology for the conductive research environment that enabled the undertaking of this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IRENA. World Energy Transitions Outlook: 1.5 °C Pathway, International Renewable Energy Agency, Abu Dhabi. 2021. Available online: https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook (accessed on 16 September 2022).
2. Li, L.; Lin, J.; Wu, N.; Xie, S.; Meng, C.; Zheng, Y.; Wang, X.; Zhao, Y. Review and Outlook on the International Renewable Energy Development. *Energy Built Environ.* **2020**, *3*, 139–157. [CrossRef]
3. Feng, Y.; Lin, H.; Ho, S.; Yan, J.; Dong, J.; Fang, S.; Huang, Y. Overview of wind power generation in China: Status and development. *Renew. Sustain. Energy Rev.* **2015**, *50*, 847–858. [CrossRef]
4. Roga, S.; Bardhan, S.; Kumar, Y.; Dubey, S.K. Recent technology and challenges of wind energy generation: A review. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102239. [CrossRef]
5. Varma, R.K.; Salehi, R. SSR Mitigation With a New Control of PV Solar Farm as STATCOM (PV-STATCOM). *IEEE Trans. Sustain. Energy* **2017**, *8*, 1473–1483. [CrossRef]
6. Kenyon, R.W.; Bossart, M.; Marković, M.; Doubleday, K.; Matsuda-Dunn, R.; Mitova, S.; Julien, S.A.; Hale, E.T.; Hodge, B.-M. Stability and control of power systems with high penetrations of inverter-based resources: An accessible review of current knowledge and open questions. *Sol. Energy* **2020**, *210*, 149–168. [CrossRef]
7. Beza, M.; Bongiorno, M. Impact of converter control strategy on low- and high-frequency resonance interactions in power-electronic dominated systems. *Int. J. Electr. Power Energy Syst.* **2020**, *120*, 105978. [CrossRef]
8. Makolo, P.; Zamora, R.; Lie, T.-T. The role of inertia for grid flexibility under high penetration of variable renewables—A review of challenges and solutions. *Renew. Sustain. Energy Rev.* **2021**, *147*, 111223. [CrossRef]
9. Shair, J.; Li, H.; Hu, J.; Xie, X. Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111111. [CrossRef]
10. Yuan, X.; Hu, J.; Cheng, S. Multi-time scale dynamics in power electronics-dominated power systems. *Front. Mech. Eng.* **2017**, *12*, 303–311. [CrossRef]
11. Hatziargyriou, N.; Milanovic, J.; Rahmann, C.; Ajjarapu, V.; Canizares, C.; Erlich, I.; Hill, D.; Hiskens, I.; Kamwa, I.; Pal, B.; et al. Definition and Classification of Power System Stability—Revisited & Extended. *IEEE Trans. Power Syst.* **2020**, *36*, 3271–3281. [CrossRef]
12. Kundur, P.; Paserba, J.; Ajjarapu, V.; Andersson, G.; Bose, A.; Canizares, C.; Hatziargyriou, N.; Hill, D.; Stankovic, A.; Taylor, C.; et al. Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions. *IEEE Trans. Power Syst.* **2004**, *19*, 1387–1401. [CrossRef]
13. erms. Terms, Definitions and Symbols for Subsynchronous Oscillations. *IEEE Trans. Power Appar. Syst.* **1985**, *PAS-104*, 1326–1334. [CrossRef]
14. Virulkar, V.; Gotmare, G. Sub-synchronous resonance in series compensated wind farm: A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 1010–1029. [CrossRef]
15. Cheng, Y.; Fan, L.; Rose, J.; Huang, F.; Schmall, J.; Wang, X.; Xie, X.; Shair, J.; Ramamurthy, J.; Modi, N.; et al. Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources. *IEEE Trans. Power Syst.* **2022**. [CrossRef]
16. Parniani, M.; Iravani, M. Voltage control stability and dynamic interaction phenomena of static VAr compensators. *IEEE Trans. Power Syst.* **1995**, *10*, 1592–1597. [CrossRef]

17. Khayyatzadeh, M.; Kazemzadeh, R. Sub-synchronous resonance damping using high penetration PV plant. *Mech. Syst. Signal Process.* **2017**, *84*, 431–444. [CrossRef]
18. Khazaei, J.; Asrari, A.; Idowu, P.; Shushekar, S. Sub-Synchronous Resonance Damping using Battery Energy Storage System. In Proceedings of the 2018 North American Power Symposium (NAPS), Fargo, ND, USA, 9–11 September 2018; pp. 1–6. [CrossRef]
19. Patil, V.S.; Thakre, M.P. Grid Integration of the Wind Power Generation and its Potential Impact on Sub-Synchronous Oscillation. In Proceedings of the 2020 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), Virtual, 10–11 December 2020; pp. 1–7. [CrossRef]
20. Reader's guide to subsynchronous resonance. *IEEE Trans. Power Syst.* **1992**, *7*, 150–157. [CrossRef]
21. Damas, R.N.; Son, Y.; Yoon, M.; Kim, S.-Y.; Choi, S. Subsynchronous Oscillation and Advanced Analysis: A Review. *IEEE Access* **2020**, *8*, 224020–224032. [CrossRef]
22. Clark, K. Overview of subsynchronous resonance related phenomena. In Proceedings of the PES T&D 2012, Orlando, FL, USA, 7–10 May 2012; pp. 1–3. [CrossRef]
23. Irwin, G.D.; Jindal, A.K.; Isaacs, A.L. Sub-synchronous control interactions between type 3 wind turbines and series compensated AC transmission systems. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–6.
24. Wang, C.; Zhou, Q.; Gao, S.; Luo, J.; Diao, J.; Zhao, H.; Bu, J. A review of recent studies on the mechanisms and analysis methods of sub-synchronous oscillation in wind farms. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *133*, 012014. [CrossRef]
25. Mohammadpour, H.A.; Santi, E. Sub-synchronous resonance analysis in DFIG-based wind farms: Definitions and problem identification Part I. In Proceedings of the 2014 IEEE Energy Conversion Congress and Exposition (ECCE), Pittsburgh, PA, USA, 14–18 September 2014; pp. 812–819. [CrossRef]
26. Shair, J.; Xie, X.; Wang, L.; Liu, W.; He, J.; Liu, H. Overview of emerging subsynchronous oscillations in practical wind power systems. *Renew. Sustain. Energy Rev.* **2018**, *99*, 159–168. [CrossRef]
27. Moharana, A.; Varma, R.K.; Seethapathy, R. Modal analysis of Type-1 wind farm connected to series compensated transmission line and LCC HVDC transmission line. In Proceedings of the 2012 IEEE Electrical Power and Energy Conference, London, ON, Canada, 10–12 October 2012; pp. 202–209. [CrossRef]
28. Moharana, A.; Varma, R.K.; Seethapathy, R. Modal Analysis of Induction Generator Based Wind Farm Connected to Series-compensated Transmission Line and Line Commutated Converter High-Voltage DC Transmission Line. *Electr. Power Components Syst.* **2014**, *42*, 612–628. [CrossRef]
29. De Prada, M.; Domínguez-García, J.L.; Mancilla-David, F.; Muljadi, E.; Singh, M.; Gomis-Bellmunt, O.; Sumper, A. Type-2 Wind Turbine with Additional Sub-synchronous Resonance Damping. In Proceedings of the 2013 IEEE Green Technologies Conference (GreenTech), Denver, CO, USA, 4–5 April 2013; pp. 226–232. [CrossRef]
30. Badrzadeh, B.; Saylors, S. Susceptibility of wind turbines to sub-synchronous control and torsional interaction. In Proceedings of the PES T&D 2012, Orlando, FL, USA, 7–10 May 2012; pp. 1–8. [CrossRef]
31. Wang, L.; Xie, X.; Jiang, Q.; Liu, H.; Li, Y.; Liu, H. Investigation of SSR in Practical DFIG-Based Wind Farms Connected to a Series-Compensated Power System. *IEEE Trans. Power Syst.* **2014**, *30*, 2772–2779. [CrossRef]
32. Jayakrishnan, S.R.; Cheriyan, E.P.; Sindhu, T.K. Identification and analysis of subsynchronous oscillations in DFIG based wind power plants. In Proceedings of the 2016 IEEE Region 10 Conference (TENCON), Singapore, 22–25 November 2016; pp. 850–853. [CrossRef]
33. Xu, Y.; Zhang, M.; Fan, L.; Miao, Z. Small-Signal Stability Analysis of Type-4 Wind in Series-Compensated Networks. *IEEE Trans. Energy Convers.* **2019**, *35*, 529–538. [CrossRef]
34. Fan, L.; Miao, Z. An Explanation of Oscillations Due to Wind Power Plants Weak Grid Interconnection. *IEEE Trans. Sustain. Energy* **2017**, *9*, 488–490. [CrossRef]
35. Zhao, S.; Li, R.; Gao, B.; Wang, N.; Song, S. Sub and Super Synchronous Oscillations between Type 4 Wind Turbines and Series Compensated AC Transmission Systems. In Proceedings of the 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 5–10 August 2018; pp. 1–5. [CrossRef]
36. Zhao, S.; Wang, N.; Li, R.; Gao, B.; Shao, B.; Song, S. Sub-synchronous control interaction between direct-drive PMSG-based wind farms and compensated grids. *Int. J. Electr. Power Energy Syst.* **2019**, *109*, 609–617. [CrossRef]
37. Liu, H.; Xie, X.; He, J.; Xu, T.; Yu, Z.; Wang, C.; Zhang, C. Subsynchronous Interaction Between Direct-Drive PMSG Based Wind Farms and Weak AC Networks. *IEEE Trans. Power Syst.* **2017**, *32*, 4708–4720. [CrossRef]
38. Gao, F.; Wu, B.; Zhang, B.; He, Q.; Wang, D.; Ba, W. The mechanism analysis of sub-synchronous oscillation in PMSG wind plants. In Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Milan, Italy, 6–9 June 2017; pp. 1–6. [CrossRef]
39. Feng, G.; Qifei, H.; Zhiguo, H.; Baohui, Z. The research of sub synchronous oscillation in PMSG wind farm. In Proceedings of the 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Xi'an, China, 25–28 October 2016; pp. 1883–1887. [CrossRef]
40. Zhao, S.; Li, R.; Gao, B.; Wang, N.; Zhang, X. Subsynchronous oscillation of PV plants integrated to weak AC networks. *IET Renew. Power Gener.* **2018**, *13*, 409–417. [CrossRef]

41. Yang, L.; Yu, Z.; Xu, T.; He, J.; Wang, C.; Pang, C. Eigenvalue analysis of subsynchronous oscillation in grid-connected PV power stations. In Proceedings of the 2017 China International Electrical and Energy Conference (CIEEC), Beijing, China, 25–27 October 2017; pp. 285–290. [CrossRef]
42. Mittapally, S.K.; Pang, C.; Renduchintala, U.K. Mitigation of Subsynchronous Resonance in power grid integrated with PV Power Station. In Proceedings of the 2018 International Conference on Power Energy, Environment and Intelligent Control (PEEIC), Greater Noida, India, 13–14 April 2018; pp. 507–511. [CrossRef]
43. Chikohora, T.E.; Oyedokun, D.T. Sub-Synchronous Resonance (SSR) in Series Compensated Networks with High Penetration of Renewable Energy Sources. In Proceedings of the 2020 International SAUPEC/RobMech/PRASA Conference, Cape Town, South Africa, 29–31 January 2020; pp. 1–6. [CrossRef]
44. Mohale, V.; Chelliah, T.R. Sub Synchronous Oscillation in Asynchronous Generators Serving to Wind and Hydro Power Systems—A Review. In Proceedings of the 2021 IEEE Industry Applications Society Annual Meeting (IAS), Vancouver, BC, Canada, 10–14 October 2021; pp. 1–7. [CrossRef]
45. Mehri, S.; Shafie-Khah, M.; Siano, P.; Moallem, M.; Mokhtari, M.; Catalão, J. Contribution of tidal power generation system for damping inter-area oscillation. *Energy Convers. Manag.* **2017**, *132*, 136–146. [CrossRef]
46. Netto, M.; Mili, L. A robust prony method for power system electromechanical modes identification. In Proceedings of the 2017 IEEE Power & Energy Society General Meeting, Chicago, IL, USA, 16–20 July 2017; pp. 1–5. [CrossRef]
47. Jain, S.K.; Singh, S.N. Exact Model Order ESPRIT Technique for Harmonics and Interharmonics Estimation. *IEEE Trans. Instrum. Meas.* **2012**, *61*, 1915–1923. [CrossRef]
48. Lu, Z.; Ji, T.Y.; Tang, W.H.; Wu, Q.H. Optimal Harmonic Estimation Using A Particle Swarm Optimizer. *IEEE Trans. Power Deliv.* **2008**, *23*, 1166–1174. [CrossRef]
49. Laila, D.S.; Messina, A.R.; Pal, B.C. A Refined Hilbert–Huang Transform With Applications to Interarea Oscillation Monitoring. *IEEE Trans. Power Syst.* **2009**, *24*, 610–620. [CrossRef]
50. Paternina, M.R.A.; Tripathy, R.K.; Zamora-Mendez, A.; Dotta, D. Identification of electromechanical oscillatory modes based on variational mode decomposition. *Electr. Power Syst. Res.* **2018**, *167*, 71–85. [CrossRef]
51. Brigham, E.O. *The Fast Fourier Transform and Its Applications*; Prentice Hall: Hoboken, NJ, USA, 1988.
52. Liu, H.; Qi, Y.; Zhao, J.; Bi, T. Data-Driven Subsynchronous Oscillation Identification Using Field Synchrophasor Measurements. *IEEE Trans. Power Deliv.* **2021**, *37*, 165–175. [CrossRef]
53. Yang, X.; Zhang, J.; Xie, X.; Xiao, X.; Gao, B.; Wang, Y. Interpolated DFT-Based Identification of Sub-Synchronous Oscillation Parameters Using Synchrophasor Data. *IEEE Trans. Smart Grid* **2019**, *11*, 2662–2675. [CrossRef]
54. Zhang, F.; Cheng, L.; Gao, W.; Huang, R. Synchrophasors-Based Identification for Subsynchronous Oscillations in Power Systems. *IEEE Trans. Smart Grid* **2018**, *10*, 2224–2233. [CrossRef]
55. Rauhala, T.; Gole, A.M.; Jarventausta, P. Detection of Subsynchronous Torsional Oscillation Frequencies Using Phasor Measurement. *IEEE Trans. Power Deliv.* **2015**, *31*, 11–19. [CrossRef]
56. Ma, Y.; Cai, D.; Yang, X.; Huang, Q. A novel SSO parameters identification technique for power grid with high proportion renewable energy using synchrophasor data. *Int. J. Electr. Power Energy Syst.* **2021**, *132*, 107131. [CrossRef]
57. Xie, X.; Liu, H.; Wang, Y.; Xu, Z.; He, J. Measurement of sub- and supersynchronous phasors in power systems with high penetration of renewables. In Proceedings of the 2016 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Minneapolis, MN, USA, 6–9 September 2016; pp. 1–5. [CrossRef]
58. Ma, Y.; Huang, Q.; Zhang, Z.; Cai, D. Application of Multisynchrosqueezing Transform for Subsynchronous Oscillation Detection Using PMU Data. *IEEE Trans. Ind. Appl.* **2021**, *57*, 2006–2013. [CrossRef]
59. Baran, M.; Kelley, A. State estimation for real-time monitoring of distribution systems. *IEEE Trans. Power Syst.* **1994**, *9*, 1601–1609. [CrossRef]
60. Monticelli, A. *State Estimation in Electric Power Systems: A Generalized Approach*; Springer: Berlin/Heidelberg, Germany, 2012.
61. Xie, X.; Zhan, Y.; Liu, H.; Li, W.; Wu, C. Wide-area monitoring and early-warning of subsynchronous oscillation in power systems with high-penetration of renewables. *Int. J. Electr. Power Energy Syst.* **2019**, *108*, 31–39. [CrossRef]
62. Qi, Y.; Xiong, W.; Wang, L.; Wu, R.; Liu, H.; Bi, T. Subsynchronous Oscillation Monitoring and Alarm Method Based on Phasor Measurements. In Proceedings of the 2020 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia), Weihai, China, 13–15 July 2020; pp. 1649–1654. [CrossRef]
63. Xiong, W.; Wang, L.; Wu, R.; Qi, Y.; Liu, H.; Bi, T. Decision Tree Based Subsynchronous Oscillation Detection and Alarm Method Using Phasor Measurement Units. In Proceedings of the 2020 IEEE Sustainable Power and Energy Conference (iSPEC), Chengdu, China, 23–25 November 2020; pp. 2448–2453. [CrossRef]
64. Sobbouhi, A.R.; Vahedi, A. Transient stability prediction of power system; a review on methods, classification and considerations. *Electr. Power Syst. Res.* **2020**, *190*, 106853. [CrossRef]
65. *IEC/IEEE 60255-118-1:2018*; IEEE/IEC International Standard—Measuring Relays and Protection Equipment—Part 118-1: Synchrophasor for Power Systems—Measurements. IEC/IEEE: Piscataway, NJ, USA, 2018; pp. 1–78. [CrossRef]
66. Nanda, P.; Panigrahi, C.; Dasgupta, A. Phasor Estimation and Modelling Techniques of PMU—A Review. *Energy Procedia* **2017**, *109*, 64–77. [CrossRef]
67. Liu, H.; Bi, T.; Chang, X.; Guo, X.; Wang, L.; Cao, C.; Yan, Q.; Li, J. Impacts of subsynchronous and supersynchronous frequency components on synchrophasor measurements. *J. Mod. Power Syst. Clean Energy* **2016**, *4*, 362–369. [CrossRef]

68. Xie, X.; Zhan, Y.; Liu, H.; Liu, C. Improved synchrophasor measurement to capture sub/super-synchronous dynamics in power systems with renewable generation. *IET Renew. Power Gener.* **2018**, *13*, 49–56. [CrossRef]
69. Varma, R.; Auddy, S. Mitigation of subsynchronous oscillations in a series compensated wind farm with static var compensator. In Proceedings of the 2006 IEEE Power Engineering Society General Meeting, Montreal, QC, Canada, 18–22 June 2006; p. 7. [CrossRef]
70. Suriyaarachchi, D.H.R.; Annakkage, U.D.; Karawita, C.; Kell, D.; Mendis, R.; Chopra, R. Application of an SVC to damp sub-synchronous interaction between wind farms and series compensated transmission lines. In Proceedings of the 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012; pp. 1–6. [CrossRef]
71. Xie, H.; de Oliveira, M.M. Mitigation of SSR in presence of wind power and series compensation by SVC. In Proceedings of the 2014 International Conference on Power System Technology, Chengdu, China, 20–22 October 2014; pp. 2819–2826. [CrossRef]
72. Amirian, M. Mitigating Sub-Synchronous Resonance Using Static Var Compensator (SVC) Enhanced with Adaptive Neuro-Fuzzy Inference Systems (ANFIS) Controller. In Proceedings of the 2019 27th Iranian Conference on Electrical Engineering (ICEE), Yazd, Iran, 30 April–2 May 2019; pp. 532–538. [CrossRef]
73. Lak, A.; Nazarpour, D.; Ghahramani, H. Novel methods with Fuzzy Logic and ANFIS controller based SVC for damping Sub-Synchronous Resonance and low-frequency power oscillation. In Proceedings of the 20th Iranian Conference on Electrical Engineering (ICEE2012), Tehran, Iran, 15–17 May 2012; pp. 450–455. [CrossRef]
74. Varma, R.K.; Semsedini, Y.; Auddy, S. Mitigation of subsynchronous oscillations in a series compensated wind farm with Thyristor Controlled Series Capacitor (TCSC). In Proceedings of the 2007 Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources, Clemson, SC, USA, 13–16 March 2007; pp. 331–337. [CrossRef]
75. Hosseini, H.; Tousi, B. Mitigating SSR in Hybrid System with Steam and Wind Turbine by TCSC. In Proceedings of the 17th Conference on Electrical Power Distribution, Tehran, Iran 2–3 May 2012; pp. 1–6.
76. Thampatty, K.S.; Nandakumar, M.; Cheriyan, E.P. Adaptive RTRL based neurocontroller for damping subsynchronous oscillations using TCSC. *Eng. Appl. Artif. Intell.* **2011**, *24*, 60–76. [CrossRef]
77. Mohammadpour, H.A.; Shin, Y.-J.; Santi, E. SSR analysis of a DFIG-based wind farm interfaced with a gate-controlled series capacitor. *IEEE Appl. Power Electron. Conf. Expo.—APEC* **2014**, 3110–3117. [CrossRef]
78. Mohammadpour, H.A.; Ghaderi, A.; Santi, E. Analysis of sub-synchronous resonance in doubly-fed induction generator-based wind farms interfaced with gate–controlled series capacitor. *IET Gener. Transm. Distrib.* **2014**, *8*, 1998–2011. [CrossRef]
79. Mohammadpour, H.A.; Santi, E. Modeling and Control of Gate-Controlled Series Capacitor Interfaced With a DFIG-Based Wind Farm. *IEEE Trans. Ind. Electron.* **2014**, *62*, 1022–1033. [CrossRef]
80. Mohammadpour, H.A.; Islam, M.; Coats, D.; Santi, E.; Shin, Y.-J. Sub-synchronous resonance mitigation in wind farms using gate-controlled series capacitor. In Proceedings of the 2013 4th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Rogers, AR, USA, 8–11 July 2013.
81. El Moursi, M.S.; Khadkikar, V. Novel control strategies for SSR mitigation and damping power system oscillations in a series compensated wind park. In Proceedings of the IECON 2012—38th Annual Conference on IEEE Industrial Electronics Society, Montreal, QC, Canada, 25–28 October 2012; pp. 5335–5342. [CrossRef]
82. Wang, C.; Liu, C.; Yu, J.; Xu, S. Research on Sub-synchronous Oscillation Characteristics between PMSG-based Wind Farms and Weak AC Grids Based on Prony Method. In Proceedings of the 2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2), Changsha, China, 8–10 November 2019; pp. 2781–2786. [CrossRef]
83. Abdou, A.F.; Abu-Siada, A.; Pota, H.R. Damping of subsynchronous oscillations and improve transient stability for wind farms. In Proceedings of the 2011 IEEE PES Innovative Smart Grid Technologies, Perth, Australia, 13–16 November 2011; pp. 1–6. [CrossRef]
84. Moharana, A.; Varma, R.K.; Seethapathy, R. SSR mitigation in wind farm connected to series compensated transmission line using STATCOM. In Proceedings of the 2012 IEEE Power Electronics and Machines in Wind Applications, Denver, CO, USA, 16–18 July 2012; pp. 1–8. [CrossRef]
85. Moharana, A.; Varma, R.K.; Seethapathy, R. Subsynchronous Impact of Series Compensation on Induction Generator Based Wind Farm. *Electr. Power Components Syst.* **2013**, *41*, 1041–1058. [CrossRef]
86. Moharana, A.; Varma, R.K.; Seethapathy, R. SSR Alleviation by STATCOM in Induction-Generator-Based Wind Farm Connected to Series Compensated Line. *IEEE Trans. Sustain. Energy* **2014**, *5*, 947–957. [CrossRef]
87. Golshannavaz, S.; Aminifar, F.; Nazarpour, D. Application of UPFC to Enhancing Oscillatory Response of Series-Compensated Wind Farm Integrations. *IEEE Trans. Smart Grid* **2014**, *5*, 1961–1968. [CrossRef]
88. Hosseini, H.; Tousi, B. Mitigating SSR in hybrid system with steam and wind turbine by UPFC. In Proceedings of the 17th Conference on Electrical Power Distribution, Tehran, Iran 2–3 May 2012; pp. 1–6.
89. Shair, J.; Xie, X.; Yan, G. Mitigating subsynchronous control interaction in wind power systems: Existing techniques and open challenges. *Renew. Sustain. Energy Rev.* **2019**, *108*, 330–346. [CrossRef]
90. Leon, A.E.; Solsona, J.A. Sub-Synchronous Interaction Damping Control for DFIG Wind Turbines. *IEEE Trans. Power Syst.* **2015**, *30*, 419–428. [CrossRef]
91. Zhu, C.; Fan, L.; Hu, M. Control and analysis of DFIG-based wind turbines in a series compensated network for SSR damping. In Proceedings of the IEEE PES General Meeting, Minneapolis, MN, USA, 25–29 July 2010; pp. 1–6. [CrossRef]

92. Faried, S.O.; Unal, I.; Rai, D.; Mahseredjian, J. Utilizing DFIG-Based Wind Farms for Damping Subsynchronous Resonance in Nearby Turbine-Generators. *IEEE Trans. Power Syst.* **2012**, *28*, 452–459. [CrossRef]
93. Mokhtari, M.; Khazaei, J.; Nazarpour, D. Sub-Synchronous Resonance damping via Doubly Fed Induction Generator. *Int. J. Electr. Power Energy Syst.* **2013**, *53*, 876–883. [CrossRef]
94. Mohammadpour, H.A.; Ghaderi, A.; Mohammadpour, H.; Santi, E. SSR damping in wind farms using observed-state feedback control of DFIG converters. *Electr. Power Syst. Res.* **2015**, *123*, 57–66. [CrossRef]
95. Li, P.; Xiong, L.; Wu, F.; Ma, M.; Wang, J. Sliding mode controller based on feedback linearization for damping of sub-synchronous control interaction in DFIG-based wind power plants. *Int. J. Electr. Power Energy Syst.* **2018**, *107*, 239–250. [CrossRef]
96. Bian, X.; Ding, Y.; Jia, Q.; Shi, L.; Zhang, X.; Lo, K.L. Mitigation of sub-synchronous control interaction of a power system with DFIG-based wind farm under multi-operating points. *IET Gener. Transm. Distrib.* **2018**, *12*, 5834–5842. [CrossRef]
97. Wu, Z.; Zhu, C.; Hu, M. Supplementary Controller Design for SSR Damping in a Series-Compensated DFIG-Based Wind Farm. *Energies* **2012**, *5*, 4481–4496. [CrossRef]
98. Chowdhury, M.A.; Mahmud, M.A. Mitigation of subsynchronous control interaction in series-compensated DFIG-based wind farms using a nonlinear partial feedback linearizing controller. In Proceedings of the 2016 IEEE Innovative Smart Grid Technologies—Asia (ISGT-Asia), Melbourne, Australia, 28 November–1 December 2016; pp. 335–340. [CrossRef]
99. Chowdhury, A.; Mahmud, A.; Shen, W.; Pota, H.R. Nonlinear Controller Design for Series-Compensated DFIG-Based Wind Farms to Mitigate Subsynchronous Control Interaction. *IEEE Trans. Energy Convers.* **2017**, *32*, 707–719. [CrossRef]
100. Huang, P.-H.; El Moursi, M.S.; Xiao, W.; Kirtley, J.L. Subsynchronous Resonance Mitigation for Series-Compensated DFIG-Based Wind Farm by Using Two-Degree-of-Freedom Control Strategy. *IEEE Trans. Power Syst.* **2014**, *30*, 1442–1454. [CrossRef]
101. Chowdhury, M.A.; Shafiullah, G.M. SSR Mitigation of Series-Compensated DFIG Wind Farms by a Nonlinear Damping Controller Using Partial Feedback Linearization. *IEEE Trans. Power Syst.* **2017**, *33*, 2528–2538. [CrossRef]
102. Karunanayake, C.; Ravishankar, J.; Dong, Z.Y. Nonlinear SSR Damping Controller for DFIG Based Wind Generators Interfaced to Series Compensated Transmission Systems. *IEEE Trans. Power Syst.* **2019**, *35*, 1156–1165. [CrossRef]
103. Wang, Y.; Wu, Q.; Yang, R.; Tao, G.; Liu, Z. H∞ current damping control of DFIG based wind farm for sub-synchronous control interaction mitigation. *Int. J. Electr. Power Energy Syst.* **2018**, *98*, 509–519. [CrossRef]
104. Liu, H.; Xie, X.; He, J.; Liu, H.; Li, Y. Damping DFIG-associated SSR by adding subsynchronous suppression filters to DFIG converter controllers. In Proceedings of the 2016 IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, USA, 17–21 July 2016; pp. 1–5. [CrossRef]
105. Liu, H.; Xie, X.; Li, Y.; Liu, H.; Hu, Y. Damping subsynchronous resonance in series-compensated wind farms by adding notch filters to DFIG controllers. In Proceedings of the 2015 IEEE Innovative Smart Grid Technologies—Asia (ISGT ASIA), Bangkok, Thailand, 3–6 November 2015; pp. 1–5. [CrossRef]
106. Wang, L.; Xie, X.; Jiang, Q.; Liu, X. Centralised solution for subsynchronous control interaction of doubly fed induction generators using voltage-sourced converter. *IET Gener. Transm. Distrib.* **2015**, *9*, 2751–2759. [CrossRef]
107. Zhang, X.; Xie, X.; Liu, H.; Li, Y. Robust subsynchronous damping control to stabilise SSR in series-compensated wind power systems. *IET Gener. Transm. Distrib.* **2019**, *13*, 337–344. [CrossRef]
108. Xie, H.; Li, B.; Heyman, C.; de Oliveira, M.M.; Monge, M. Subsynchronous resonance characteristics in presence of doubly-fed induction generator and series compensation and mitigation of subsynchronous resonance by proper control of series capacitor. *IET Renew. Power Gener.* **2014**, *8*, 411–421. [CrossRef]
109. Lawrence, C.; Gross, J.P. Sub-synchronous grid conditions: New event, new problem, and new solutions. In Proceedings of the 37th Annual Western Protective Relay Conference, Spokane, Washington, DC, USA, 19–21 October 2010.
110. Narendra, K.; Fedirchuk, D.; Midence, R.; Zhang, N.; Mulawarman, A.; Mysore, P.; Sood, V. New microprocessor based relay to monitor and protect power systems against sub-harmonics. In Proceedings of the 2011 IEEE Electrical Power and Energy Conference, Winnipeg, MB, Canada, 3–5 October 2011; pp. 438–443. [CrossRef]