Review on Oscillatory Stability in Power Grids With Renewable Energy Sources: Monitoring, Analysis, and Control Using Synchrophasor Technology

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***Abstract*—Oscillatory stability has received immense attention in recent years due to the significant increase in power electronic converter (PEC)-interfaced renewable energy sources. Synchrophasor technology offers superior capability to measure and monitor power systems in real time, and power system operators require better understanding of how it can be used to effectively analyze and control oscillations. This article reviews state-of-the-art oscillatory stability monitoring, analysis, and control techniques reported in the published literature based on synchrophasor technology. An updated classification is presented for power system oscillations with a special emphasis on oscillations induced from PEC-interfaced renewable energy generation. Oscillatory stability analysis techniques based on synchrophasor technology are well established in power system engineering, but further research is required to effectively utilize synchrophasor-based oscillatory stability monitoring, analysis, and control techniques to characterize and mitigate PEC-induced oscillations. In particular, emerging big data analytics techniques could be used on synchrophasor data streams to develop oscillatory stability monitoring, analysis, and damping techniques.**

***Index Terms*—Big data analytics, oscillation analysis, oscillation damping, oscillatory stability, phasor measurement unit (PMU), renewable energy sources (RESs), smart grids, synchrophasor.**

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I. Introduction

THE power system landscape is evolving rapidly with the large-scale integration of power electronic converter (PEC)-interfaced renewable energy generators, PEC-interfaced loads, and smart grid technologies [1], [2]. This ongoing transformation has a significant impact on power system operation, dynamics, and stability, and new challenges are emerging for system operators to maintain a reliable and resilient power grid. Frequency regulation/control, voltage control, oscillatory stability, and power quality (e.g., harmonics, flicker) are some of the issues pertinent to this evolving power grid [3].

Among these new challenges, power system oscillatory stability issues have received increased attention over the past few years as more PEC-interfaced renewable energy generators [e.g., doubly fed induction generators (DFIGs) and permanent magnet synchronous generators], and nonlinear loads (e.g., variable-speed drives, switch-mode power supplies, light-emitting diode drives) are connected to the power grid and reduce its damping performance [4]. This adversely influences power system oscillatory stability; hence, power system operators require an in-depth understanding of oscillation monitoring as well as analytical techniques to effectively control and manage the oscillatory stability issues. Moreover, oscillatory stability incidents have reported in power networks with significant PEC-interfaced renewable generation [5]. These incidents have also necessitated more advanced monitoring, analysis, and control techniques to mitigate such incidents in future.

Synchrophasor technology has evolved rapidly during the last two decades to become the most reliable power system monitoring technology, superseding the conventional supervisory control and data acquisition (SCADA) systems. The synchrophasor technology is now being widely deployed in power networks for power system monitoring, measurement, and control [6]. High accuracy and high-speed data transfer are two key advantages of synchrophasor technology over conventional SCADA systems [7]. Synchrophasor measurement devices are commonly known as phasor measurement units (PMUs), and this technology has many applications [6] in the power systems industry. Thus, the capability of synchrophasor technology can be harnessed to

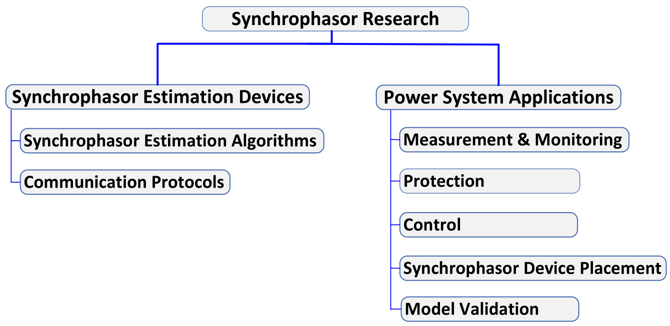

Fig. 1. Classification of synchrophasor research studies.

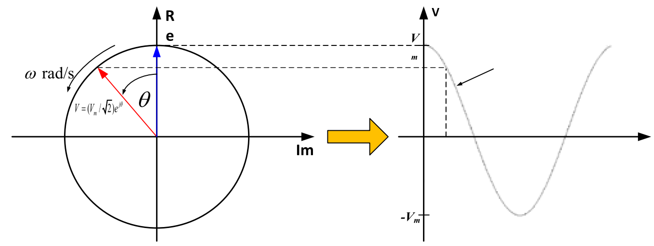

Fig. 2. Synchrophasor representation of a signal $v(t)$.

effectively monitor, analyze, and control oscillations induced by the PEC-interfaced renewables.

This article critically reviews the state-of-the-art for power system oscillation monitoring, analysis, and control techniques based on synchrophasor technology, with special emphasis on emerging oscillatory stability issues from PEC-interfaced renewable generation. In addition, it highlights current trends and future research directions for oscillatory stability monitoring and control using synchrophasor technology.

II. General Overview of Synchrophasor Technology

Research studies associated with synchrophasor measurement systems can be broadly categorized into those addressing synchrophasor estimation devices and those concerned with synchrophasor applications in power systems, as shown in Fig. 1.

Research studies on synchrophasor estimation devices primarily focus on the accuracy and latency improvements of synchrophasor algorithms and communication protocols [6], whereas those on power system applications focus on the utilization of synchrophasor data for protection schemes, stability assessment, state estimation, fault detection, wide-area oscillation damping control, planning and placement of synchrophasor devices in wide-area measurement systems in power grids, and model validation [6].

A. Definition of Phasors and Synchrophasors

A phasor is defined as a complex quantity that represents both the magnitude and phase of a sinusoidal waveform at a given instant of time. In phasor format, this sinusoidal voltage waveform $v(t)$ can be represented as follows:

$$V = (V_m/\sqrt{2})e^{j\theta}. \tag{1}$$

According to the IEC/IEEE definition (IEC/IEEE 60255-118-1:2018 [8]), a "synchrophasor" is defined as a representation of a phasor, as defined by (2), where θ is the instantaneous phase angle relative to a cosine function at the nominal system frequency (f_0) synchronized to coordinated universal time (UTC) [8], [9]. The reference cosine function has its maximum (i.e., V_m) at $t = 0$ [1 pulse per-second (PPS)]. The definition of a synchrophasor is illustrated in Fig. 2.

The measured voltage waveform $v(t)$ can be represented in synchrophasor format as follows:

$$v(t) = \left(\frac{V_m(t)}{\sqrt{2}}\right) e^{j(2\pi \int g dt + \theta)}. \tag{2}$$

If the frequency difference ($g(t)$) between the actual and nominal frequencies is a constant (Δf), then the phase angles of the sequence of phasors will change at a rate of $2\pi\Delta f\,(1/f_0)$.

These reported angles will then continuously increase with time until they reach 180° and wrap around to −180°. The synchrophasor is usually reported in angles between 180° and −180°. As synchrophasor measurements are taken based on a common time reference (i.e., UTC), they can be used for real-time monitoring of power systems; in particular, these measurements are directly comparable [9]. Synchrophasor measurements also capture waveform information, such as frequency, rate-of-change-of-frequency (ROCOF) local frequency swings, and oscillations. These parameters are usually extracted after voltage/current phasor estimation using additional algorithms [9], [10].

Typically, oscillations emanating from various power system sources and induced due to various phenomena will be superimposed on the main power frequency waveform. Impacts due to these oscillations can be realized as either phase angle modulation or magnitude modulation or both [11]. For example, the influence of phase angle and magnitude modulation on the phasor can be, respectively, represented as follows:

$$v(t) = \left(\frac{V_m(t)}{\sqrt{2}}\right) e^{j(2\pi \int g dt + \theta(1 + v_p e^{j\omega_p(t)}))}$$
$$v(t) = \left(1 + v_s e^{j\omega_s(t)}\right)\left(\frac{V_m(t)}{\sqrt{2}}\right) e^{j(2\pi \int g dt + \theta)} \tag{3}$$

where v_p, v_s, ω_p, and ω_s, respectively, denote the phase angle modulation factor, magnitude modulation factor, phase angle modulation frequency, and magnitude modulation frequency, respectively.

B. Synchrophasor Technology

The synchrophasor technology was first standardized by the IEEE Standard 1344-1995 [12], and subsequently, it was evolved into IEEE Standard C37.118.1-2005 [13] and IEEE Standard C37.118.1-2011 [9]. Most recently, IEEE Standard C37.118.1-2011 superseded by IEC/IEEE 60255-118-1:2018 [8], which stipulates the requirements satisfied by the synchrophasor measurement devices.

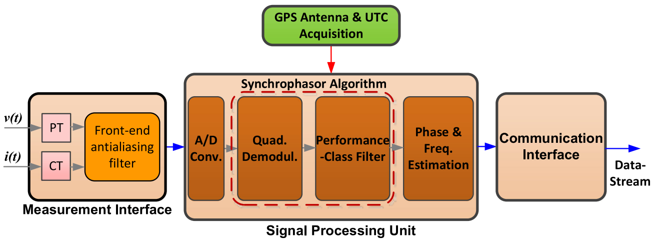

Fig. 3. Typical elements of a PMU.

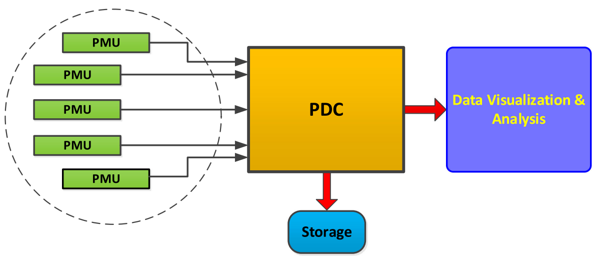

Fig. 4. Architecture of a PDC.

A synchrophasor measuring device is commonly known as a PMU and consists of several components, such as the measurement interface, signal processing unit, global position system (GPS) antenna and UTC acquisition, and communication interface (see Fig. 3) [8].

The measurement interface is usually an analog interface and may contain an analog filter at the front end (i.e., low-pass antialiasing filter). Captured signals (i.e., voltage ($v(t)$) and current ($i(t)$) signals) from the measurement interface [e.g., potential transformer (PT) and current transformer (CT)] are subsequently sent to the signal processing unit where they are processed through an analog-to-digital converter. Analog-to-digital (A/D) conversion is done based on a synchronized clock (i.e., UTC), and then a phasor measurement algorithm (i.e., synchrophasor algorithm) subsequently extracts the phasor data from the measured signal. The published literature reports many phasor measurement algorithms, such as quadrature demodulation, discrete Fourier transform (DFT), phase-locked loop (PLL), z-transform, Kalman filtering [6], [14]. The PLL is the fastest phasor estimation algorithm; however, its accuracy decreases under harmonic distortions, whereas the quadrature demodulation method is a very accurate algorithm even under such conditions [15]. The majority of the commercial PMU implementations are based on the DFT technique or its variants [16].

Accuracy of synchrophasor measurement is mainly evaluated by the total vector error (TVE), which determines the accuracy of the phasor measurement against the magnitude and phase of the input signal. IEC/IEEE 60255-118-1:2018 [8] specifies a range of static and dynamic compliance requirements to which synchrophasor devices should adhere.

C. PMU-Based Monitoring Networks

The synchrophasor data measured from each PMU are communicated to a central location [i.e., phasor data concentrator (PDC)] with a timestamp for each data point based on the protocol defined in IEC/IEEE 60255-118-1:2018 [8]. Synchrophasor data are mainly transferred via internet protocol over Ethernet at a specified reporting rate to a central location (e.g., control centre). The device that collates the synchrophasor data from various parts of the network is commonly known as the PDC (see Fig. 4. In network control centres, the synchrophasor data streams stored by PDCs are used for real-time situational awareness applications, e.g., real-time voltage stability, oscillatory stability, transient stability, etc. [17], [18].

Multiple PDCs are typically employed for power networks spread across a large geographical area in a hierarchical manner. The PDCs located at the bottomof the hierarchy are called the local PDCs, and the data collated at these local PDCs are sent to regional PDCs. The data collated at regional PDCs are sent to central/corporate PDCs.

D. Capabilities and Limitations

Synchrophasor units typically report at the power frequency (e.g., 50 Hz); however, IEC/IEEE 60255-118-1:2018 also allows low reporting rates, such as 10 and 25 Hz, and high reporting rates, such as 100 Hz, for 50-Hz systems [8]. The reliability of the communication protocol (e.g., asymmetric digital subscriber line, fourth generation, worldwide interoperability for microwave access, etc.) associated with the synchrophasor network directly affects the measurement quality [7]. Typically, latency and packet loss are the main issues associated with the communication protocol [19]. The latency is an important parameter for real-time stability monitoring and depends on several factors, such as delays associated with measurement system filtering, phasor measurement algorithms, and communication channel bandwidth. The communication channel bandwidth is the main contributing factor for the latency. In addition, packet loss also affects the quality of the data acquired by the synchrophasor network. Research studies have estimated the impact of latency and packet loss on synchrophasor data streams and developed strategies to deal with these issues [20]–[23]. In addition to the communication-protocol-related issues, synchrophasor measurements are also affected by the noise and bias errors; hence, synchrophasor measurement devices must be calibrated to ensure the fidelity of the phasor measurement. The literature reports various calibration methods, such as adaptive nonlinear state estimation [24] and density-based spatial clustering [25].

III. Classification and New Challenges of Power System Oscillations

A. Classification of Power System Oscillations

Power system oscillations, usually in the form of power oscillation, can be triggered by a variety of factors, such as variations in load and renewable power generation, torsional resonance, and converter control system switching. Power systems normally cannot avoid these triggering factors and are stable if the occurring oscillations can be controlled and eventually suppressed. On the contrary, if the magnitude of oscillations continues to increase or is sustained indefinitely, then so-called oscillatory instability appears. Therefore, power systems

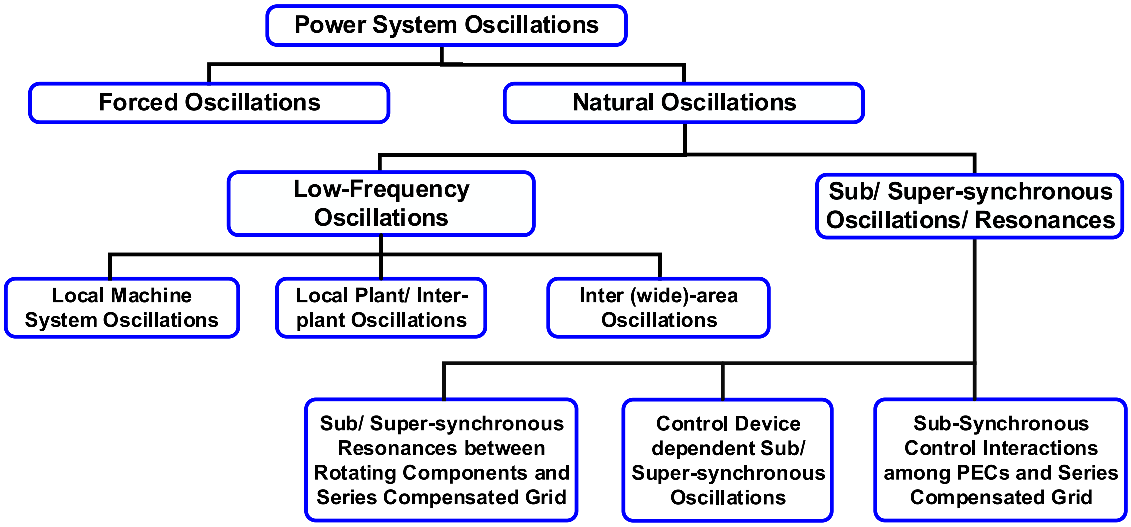

Fig. 5. Classification of power system oscillations.

should always be able to operate against continuous oscillations [26].

Apart from the forced oscillation associated with cyclic oscillating sources, natural power system oscillations can generally be classified into two major categories according to the different oscillatory frequency ranges and mechanisms: low-frequency oscillation (LFO) and sub-/supersynchronous oscillation/resonance (SSO/SSR) [27]. The former mainly involves synchronous generators (SGs) and can be further classified into the following three subcategories based on the typical frequency [27], [28].

1) Local machine system oscillations (one SG or a group of coherent SGs against the whole strong power system or load centre, 0.7–3.0 Hz).
2) Local plant/interplant oscillations (two or more SGs in the same power plant or nearby power plant against one another, 0.7–3.0 Hz).
3) Inter (Wide)-area oscillations (a group of coherent SGs in one area against another group of coherent SGs located in another area of a wide-area power system, 0.1–0.7 Hz).

In contrast to LFO, SSO/SSR has a wide range of oscillatory frequencies due to the sophisticated causes, and classification is normally based on the participating equipment. Classification has undergone a dynamic development process, and quite a few amendments have been made by the SSR working group of the IEEE Power System Dynamic Performance subcommittee. Since the year 1976, when the first SSO/SSR classification report [29] was produced by the SSR working group, four supplementary reports [30]–[33] were then produced in 1979, 1985, 1991 and 1997, respectively. Apart from those reports, two new SSO/SSR definition and classification reports [34], [35] were also produced in 1985 and 1992, respectively. Recently, owing to the increasing integration of converter-interfaced equipment, such as wind and solar power generation, emerging types of SSO/SSR are continuously being observed [36], [37], which are essentially different from the previously defined SSO/SSR subcategories. Therefore, considering the existing classification and the various newly observed oscillations affected by PEC-interfaced systems, SSO/SSR can be reclassified into three subcategories:

1) SSR between rotating components and a series compensated grid [induction generator/machine effect, torque amplification, and torsional interaction (TI)];
2) control-device-dependent SSO (steam-/hydroturbine against fast response controllers, so-called subsynchronous TI);
3) subsynchronous control interaction (SSCI) among PECs and series compensated grids.

As SSCI is a novel type of SSO/SSR, the essential mechanism of such interactions and how to damp them remain open questions for grid connection of PEC systems. In summary, an illustrative diagram for the classification of power system oscillations is presented in Fig. 5.

B. Oscillation Issues in Renewable-Rich Power Networks

For the sustainable development of society and economics, conventional fossil-fuel-based generators are expected to be gradually decommissioned and replaced by a growing amount of renewable power generation (e.g., wind and solar) in many countries and regions. As a result, modern power system dynamics, especially oscillatory characteristics, have been significantly affected by the high penetration of renewables with respect to two main aspects.

1) With the rapid development of renewable energy sources (RESs), increasing amounts of PEC-connected equipment have penetrated into conventional power systems, which enhances system flexibility and controllability [38]–[41] but also considerably complicates the dynamic behaviour of both transmission and distribution systems and causes complex oscillatory stability problems [42]–[47].

2) The intermittence and fluctuation of large numbers of RESs bring massive uncertainties to the stability margin of different oscillatory problems [45], e.g., LFO and SSO/SSR, as their nature means the system operational status continuously changes.

On the one hand, the PEC system participates in the existing conventional power oscillations (e.g., LFO) and makes the problems more complex [46], [47]; on the other hand, it also brings some new types of oscillations and frequent interactions among different types of RES PECs or between the RES PECs and weak power grid with different voltage levels, which are very different in nature from the LFO problem. For instance, an SSR with a resonant frequency of 20 Hz occurred between the DFIG-based wind farm and series compensation of the power grid in Texas (USA), which caused crowbar damage and disconnection of several DFIGs in 2009. Severe sub-/supersynchronous oscillations among full converter-based wind generators were observed in Xinjiang (China), which caused the trip of a large power plant as well as an ultra-high-voltage direct current (HVdc) system in 2015. According to historical records, many more under/overfrequency oscillations are observed in wind-farm-connected systems, the dynamics of which are associated with PECs rather than the system or wind turbine. Exactly how such oscillations happen and how to damp them remain open problems for grid connections of wind power. Therefore, emerging oscillations together with existing oscillation problems introduce considerable complexities to operational assessment, pose a very serious threat to the operational security of modern power systems, and could result in critical system accidents and enormous losses. There is a pressing need to carefully investigate these important oscillatory issues in renewable-rich power networks and provide effective solutions to the power system operators.

IV. Synchrophasor-Based Oscillation Monitoring and Analysis Methods

Traditional methods to analyze oscillatory stability mainly include modal analysis in the frequency domain and nonlinear simulation in the time domain, both of which heavily rely on the accuracy of system dynamic models and thus are also named "model-based" methods [27]. However, with the integration of large numbers of RES PECs, system dynamic modeling encounters critical challenges. Large quantities of PEC systems with complex structures, time-varying parameters, and "black-box" controllers not only make system modeling nearly an impossible task, but also significantly increase model dimension and computational burden, especially for a resource-constrained real-time operation. Hence, due to these "new features," traditional methods might be no longer suitable for a modern system operation. Moreover, traditional model-based methods face some practical limitations. Different levels of modeling adequacy and complexity are required to deal with different oscillation/resonance problems. Additionally, different power system commercial packages might be employed for offline and online studies in some utilities (e.g., PowerFactory DIgSILENT is used for offline planning whereas PowerTech DSA is used for online operation by National Grid UK). Hence, the unavoidable inconsistency of dynamic models built in different packages often leads to inevitable discrepancies in the stability analysis results, which complicates the dynamic issue, aggravates the analysis burden, and requires extra work in terms of model validation.

The deployment of PMUs with a high sampling rate at many critical terminals of the system enables the real-time monitoring of power system dynamics, which provides important information for oscillatory stability assessment and enhancement. If both the quantity and quality of the measured data are sufficient to primarily support the assessment, the approach can be named data-based oscillatory stability analysis. This approach is superior due to the boost of data analytics capability over the traditional model-based analysis for dealing with the new smart grid environment characterized by PEC systems and can provide an effective solution to the abovementioned challenges. The application of data-based oscillatory stability analysis can generally be divided into two categories: estimating the target oscillation mode/mode shape at the system level and tracking the energy flow of system components at the device level. The following review regarding the existing data-based techniques in oscillatory stability analysis is carried out with respect to these two aspects.

A. Oscillation Mode/Mode Shape Monitoring and Estimation

Since the failure of model-based methods to identify the unstable oscillation mode of the 1996 outage in the USA [48], an increasing number of methods, from signal processing to system identification to artificial intelligence, have been used to monitor and estimate the modal properties of oscillations, including oscillatory frequency, damping ratio, and mode shape [49]. Initial efforts were devoted to the estimation of oscillation mode (i.e., frequency and damping) as it is directly associated with the stability margin. By using the ringdown (postfault) data, some estimation methods, such as Prony analysis [50], minimal realization [51], eigensystem realization [52], Fourier transformation, Hilbert–Hung transformation [53], matrix pencil [54], wavelet transformation, variable projection [55], and PLL, were developed. Because the system usually operates under normal conditions, other estimation methods suitable for ambient data have also been proposed, including spectral analysis [56], the Yule–Walker method [57], frequency-domain decomposition [58], and the autoregressive moving average exogenous (ARMAX) model [59]. The recursive method (least mean squares adaptive filtering [60] and robust recursive least squares [61]) and subspace system identification [62] are applicable for both data types.

On the contrary, the estimation of mode shape to facilitate deeper understanding about the oscillation and provide useful information for damping control was recently developed, with methods including the continuous modal parameter estimator [63], principal component analysis [64], Prony analysis, moment-matching method [65], matrix pencil [66], Kalman filtering [67], and PLL method for ringdown data as well as cross-spectrum analysis [68], frequency-domain decomposition [51], channel-matching method [69], transfer function [70], and ARMAX model [59] for ambient data. Stochastic subspace system identification proposed in [71] is applicable for both types of data. Note that Prony analysis, frequency-domain decomposition, PLL method, ARMAX model, matrix pencil, and subspace system identification can be employed for both mode and mode shape estimation; however, only subspace system identification can accommodate both ringdown and ambient data conditions, but this requires considerable computational resources.

Therefore, some observations on the current research and techniques are summarized.

1) Most research targets the conventional electromechanical oscillation modes (e.g., LFO), and few studies or data-based estimation techniques tackle the new oscillation modes induced by the PEC systems (e.g., power resonance due to the interaction between renewables and voltage-source converters, HVdc controllers, and forced oscillations brought by the fluctuation of renewables).
2) Few data-based estimation methods can be adapted to both ringdown and ambient data conditions.
3) The oscillation sources are indirectly identified by the estimated mode shape (i.e., major SGs associated with the oscillation modes), which cannot actually achieve 100% accuracy and hinder a better understanding of the oscillation issues.
4) Most research assumes that the PMU measurement is fully available and correct and does not consider data security and quality issues, which could significantly affect the monitoring and estimation performance.
5) The existing monitoring and estimation tools are essentially based on modal analysis, which deal with a large amount of data and matrices, perform like a "black box," and cannot dig for further information of essential oscillation mechanisms to reveal how the damping contribution is distributed and transmitted from the damping source (e.g., damping controller) to the specific oscillation mode and facilitate the understanding of power system operators [72]–[74]. Hence, they strictly function to monitor and estimate rather than as an analysis tool and do not offer any assessment support from the device level.

B. Energy Flow Tracking Based on Measurement Data

The other type of data-based method in oscillatory stability analysis is energy flow tracking and assessment at the device level. If a device is connected to the system by a branch *ij* at terminal *i*, the oscillation energy flow from the device to the branch can be obtained as follows [75]:

$$W_{ij} = \int P_{ij} d\theta_{ij} + \frac{Q_{ij}}{U_i} dU_i \tag{4}$$

where P_{ij} and Q_{ij} are the active and reactive powers from terminal *i* to terminal *j*, respectively, θ_{ij} is the voltage angle difference between terminals *i* and *j*, and U_i is the voltage magnitude of terminal *i*. P_{ij}, Q_{ij}, U_i, and θ_{ij} can be measured directly. It is rigorously proven in [75] that if the device mentioned above is an SG, the oscillation energy dissipation $(dW_{ij})/dt$ should be equal to the damping torque of the SG for a single-machine infinite bus system, and hence the method can provide power system operators a clear physical understanding of the oscillation problems. On this basis, Xie and Trudnowski [76] further developed a practical method based on the ambient measurement data that can be applied to any system device. By employing Parseval's theory, the damping torque coefficient provided by the system device can be computed as follows:

$$K_{D,i}(f) = \text{Real}\left[\frac{S_{\Delta P_{ij},\Delta\omega_i}(f) + S_{\Delta Q_{ij},\Delta\dot{U}_i}(f)}{S_{\Delta\omega_i,\Delta\omega_i}(f)}\right] \tag{5}$$

where $S_{x_1,x_2}(f)$ is the cross-energy spectral density of $x_1(t)$ and $x_2(t)$, and ω_i is the angular speed of the voltage at terminal *i*. Using (5), the contribution from any local component to the damping of any power oscillation over a wide frequency range can be analyzed.

The abovementioned oscillation energy flow methods have been recently developed with the aid of continuous deployment of PMUs for major source devices and have quite a few merits, such as the following.

1) The computation of energy flow is straightforward and efficient and is very suitable for online monitoring and visualization of power oscillation and resonance.
2) This method makes it easy to accurately detect the oscillation source (with negative energy dissipation) and identify the real cause of the oscillation regardless of the type of energy sources.
3) As any oscillation problem is essentially reflected as energy flow fluctuation, energy flow tracking and assessment can be applied to tackle any type of oscillation problem in transmission and distribution systems.

Therefore, it is reasonable to believe that the method can be also employed to solve oscillation problems associated with PECs.

However, unlike the definition of "stability" in power electronics, power system stability is usually a global problem, e.g., power system oscillatory stability. The oscillation/resonance modes normally involve multiple separate oscillating participants rather than just one SG or PEC. Tracking local energy flow is not sufficient to obtain a full picture and thus effectively solve the system-level oscillation problems from the power system operator's perspective. Although the consistency of energy dissipation with the damping torque of a generator has been well proven in a single-machine infinite bus system, it is technically difficult to extend the rigorous proof to a multimachine power system [77] and raise the energy flow assessment to the system level. As a result, this method is still limited to local applications, and the connection between the local damping contribution and system oscillatory stability margin is missing. Moreover, the synchrophasor technology-based wide-area measurement system (WAMS) is still under development and most power systems do not yet have 100% observability.

C. SSO Monitoring and Analysis Methods

According to the literature, monitoring of subsynchronous oscillations was not attractive compared with interarea oscillations in the early years after the introduction of synchrophasor technology for power system applications. However, the observability of subsynchronous oscillations in synchrophasor measurements is possible with the increased output rates of phasor measurements (e.g., 100 or 120 Hz). Rauhala *et al.* [78] theoretically showed the variation of the fundamental phasor of voltage and current signals in the presence of subsynchronous oscillations in the system.

In this context, researchers have demonstrated that the same algorithms for LFO monitoring can be used to detect subsynchronous oscillations with few adjustments. The main objective of an oscillation monitoring algorithm is therefore to extract the frequency, damping, amplitude, and phase angle parameters. Among them, frequency and damping are the key parameters from a system stability point of view. Prony, Hankel total least squares, eigen realization, and matrix pencil are four commonly used time-domain parametric methods to determine the modal parameters in online and offline environments. These four methods differ with respect to the manner in which the least squares solution is obtained by processing the samples stored in a data matrix. Furthermore, the modal parameters can also be determined by subjecting the abovemenyioned equation to Fourier transform and processing the signal in the frequency domain. Tashman *et al*. [79] showed that the frequency and damping of both low-frequency and subsynchronous oscillations can be extracted using a multidimensional Fourier analysis of a ringdown response. It also shows that the Prony, Hankel total least squares, eigen realization, and matrix pencil methods can also be accurately used for the abovementioned purpose.

As experienced in subsynchronous oscillation-based incidents, supersynchronous interharmonics can also present in voltage and current signals in addition to subsynchronous interharmonics [80]. However, considering the maximum reporting rate of either 100 or 120 samples per second [8], the supersynchronous oscillations are not visible in conventional PMU measurements. Thus, such oscillations can be only observed in real time by modifying the conventional DFT-based phasor estimation algorithm in PMUs. Several attempts in this regard can be found in the literature. In [81], an interharmonic identification method is proposed by applying fast Fourier transform (FFT) with zero-padding on complex phasor sequences of PMUs. A similar approach is proposed in [82], in which the sub-/supersynchronous harmonic components are extracted using an FFT algorithm with the Grandke ratio method to correct spectral leakage in the FFT algorithm. The conventional DFT-based phasor calculation and three-point correction algorithm are used in [83] to estimate both fundamental and interharmonic phasors. In [84], a synchronized measurement device (SMD) called SMD-R is developed and experimentally validated for use in inverter-based renewable rich networks to measure both fundamental and interharmonic phasors in real time using an improved FFT algorithm. A recent publication, [80], proposes an improved iterative Taylor–Fourier multifrequency (I2TFM) phasor estimator to accurately extract model parameters of both fundamental and sub-/supersynchronous oscillations. The TVE and the frequency error are shown to be less in the I2TFM algorithm developed.

Real-time monitoring of supersynchronous oscillations is only possible by modifying the conventional phasor estimation algorithm as highlighted above. This leads to new research opportunities in real-time situational awareness in future renewable integrated power systems.

V. Synchrophasor-Based Oscillation Damping Systems

Interarea, interplant, or even subsynchronous oscillatory modes limit power transfer along the lines when they are poorly damped and can lead to a failure in the system when they are unstable. Therefore, real-time monitoring of power system oscillations and initiating preventive control actions when they are not acceptable are topics that have been receiving increased attention from the research community. In this regard, the majority of the related literature describes different algorithms for controlling interarea oscillations using synchrophasor measurements. This is due to the fact that the unstable interarea oscillations lead to widespread failures because they involve the oscillations of groups of generators located in different regions of the network.

Insufficient damping of interarea oscillations is identified as a small-signal stability problem in power systems [85]. Traditionally, this stability problem has therefore been controlled using a properly tuned power system stabiliser (PSS) that provides an auxiliary controlling signal to an automatic voltage regulator [19]. The use of a linearized model to design PSSs and hence to solve the small-signal stability problem creates challenges related to the

1) validity of the linear model about multiple operating points,
2) robustness and adaptability of the designed controllers to work under multiple operating conditions,
3) model uncertainties,
4) size and associated computational complexities of the state matrix of larger power systems.

Another limitation of conventional PSS as reported in literature is its inability to provide adequate damping simultaneously for local and interarea oscillatory modes. In order to address this issue, a modern multiband PSS (PSS4B) is proposed in [86]. A hierarchical two-stage control strategy using synchrophasor data is proposed in [87] to design a multistage PSS. Despite all these limitations, PSSs designed using local signals [88] may not properly damp interarea oscillations because such oscillations involve generators that are geographically spread out in larger areas. In this context, the availability of synchrophasor measurements and hence the remote signals from widely dispersed locations in a power system play an important role in designing wide-area damping controllers.

The majority of existing synchrophasor-based wide-area damping controllers fall under the category of robust and adaptive controllers. These controllers are designed with the objective of handling the model uncertainties and adaptively upgrading under vast operating conditions of the power system. Thus, they are much better than traditional linear controllers. Some of these robust and adaptive controllers are the H_∞ controller, multiagent H_∞ controller [89], mixed H_2/H_∞ controller [90], dual Youla parameterization-based adaptive controller [91], and multipolytopic adaptive controller [92]. The accurate damping controlling of the abovementioned techniques has been demonstrated in the literature using simulated signals for different test systems under different operating conditions. In r [93], few of these wide-area damping controller design techniques are compared against some properties, such as robustness and calculation cost.

A challenge when using remote signals for damping controllers is the inherent communication delays, which may be due to network-induced delays, data dropout, etc. These inherent delays have been considered as model uncertainty in some literature [94]. Later research reports that the controllers can be designed by compensating for the communication delay even at the design stage. The networked predictive control approach [95], phasor power oscillation damping (POD) controller [96], enhanced adaptive phasor POD controller [97], Smith-predictor-based H_∞ controller [98], recurrent-neural-network-based controller [99], and stochastic-subspace-identification-based controller [100] are examples of such controllers. Another category of synchrophasor-based damping controller is designed using flexible alternating current transmission system (FACTS) devices, such as the wide-area damping controller designed using a thyristor-controlled series capacitor [101] and the adaptive neuro-fuzzy static VAr compensator (SVC) controller [102].

VI. Synchrophasor-Based Oscillation Monitoring and Control Systems in Power Grids

Synchrophasor-based wide-area oscillation monitoring and control systems are emerging in power grids around the world due to the high accuracy and significantly improved reporting rates they offered by synchrophasor systems. Table I summarizes the features of various synchrophasor-based oscillatory stability monitoring systems implemented in power grids around the world.

One of the earliest PMU-based oscillation monitoring systems was the Statnett power oscillation monitoring system [103]–[105], which was implemented in parallel with the existing SCADA system. Early on, the synchrophasor data were not sufficient for the PSSs to use for oscillation damping, although the system was able to capture and analyze oscillations in real time [103]. Subsequently, the Statnett power oscillation monitoring system was improved to damp interarea mode oscillations (e.g., 0.48 Hz mode) using SVCs [104]. The architecture of the Statnett power oscillation monitoring and damping control system is shown in Fig. 6.

The Statnett POD control system designed for the SVC has the capability to choose the damping signal from either the local damping controller or the WAMS-based controller signal (i.e., wide-area POD control). Therefore, if the WAMS-based damping signal is lost or unreliable, then the control system will automatically switch over to the local damping controller [104].

TABLE I
PMU-Based Oscillation Monitoring Systems in Power Grids

WAMS System	Network	Techniques	Monitored Oscillation Frequencies	Oscillation Type
Statnett Power Oscillation Monitoring System [103]–[105]	Nordic Power Network	Autoregressive model and Kalman filtering	0.33 Hz, 0.48 Hz, 0.62 Hz (IAM) 0.55 Hz, 0.76 Hz (LAM)	inter-area modes (IAM), local-area modes (LAM)
SGCC WAMS platform [106]	China	Energy function method and autoregressive moving average (ARMA)	0.1-0.2 Hz (IAM) 0.7-2.5 Hz (LAM)	IAM, LAM
Swissgrid WAMS [107]	Swissgrid	Sliding window with modal analysis	0.13-0.27 Hz (IAM) 0.9-2 Hz (LAM)	IAM, LAM
Southern California Edison Company [108]	Southern California	-	0 to 1.5 Hz	-
Manitoba Hydro [19]	Manitoba	-	0.1 to 0.3 Hz	-
Tennessee Valley[109]	Knoxville, Tennessee	Prony analysis	1.2 Hz (LAM)	LAM

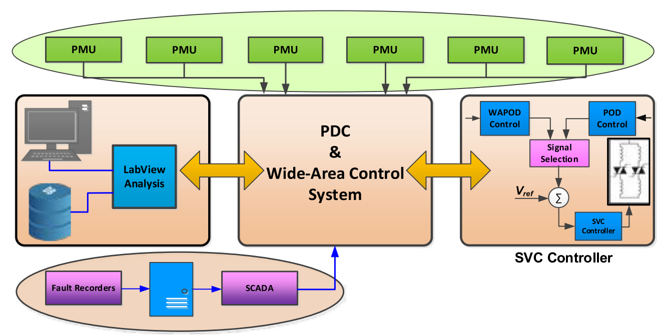

Fig. 6. Architecture of the Statnett power oscillation monitoring and damping system [104].

The Statnett oscillation damping system has proven to be reliable under communication latencies up to 200–300 ms [104].

VII. Wide-Area Monitoring and Analysis Using Big Data Analytics

Big data analytics is becoming a very active research area in synchrophasor measurement networks, as a large amount of synchrophasor data accumulates in synchrophasor networks due to high sampling rates [110]–[111]. Big data analytics is applied to large databases to efficiently process and extract various information within a quick turnaround time. "Big data" is characterized by three-main features [112]—volume, variety, and velocity—and the data produced by phasor measurement networks satisfy these characteristics. According to Akhavan-Hejazi and Mohsenian-Rad [110], the big data analytics applied to synchrophasor measurements can be broadly divided into four major types:

1) dynamic event detection;
2) data mining in large databases;
3) advanced statistics;

4) scale-up and parallel processing.

A. Dynamic Event Detection

These algorithms are designed for large streams of synchrophasor data for real-time detection of dynamic events in power networks [113]–[115]. In [113], Tate proposed to continually check the signal against a threshold value after the signal is filtered by a finite impulse response filter. In addition, they proposed a dynamic line outage detection algorithm using synchrophasor data streams and used fast-forward and fast-backward solutions to reduce the computational burden. An offline hierarchical clustering approach was proposed in [114] for coherent groups of generators to detect the event location. The authors used the individual generator rotor angles extracted from PMU data, with the method proving to be more than 80% accurate in locating an event. The detrended fluctuation analysis (DFA) technique was proposed in [115] to detect various transient events in the network. The DFA technique has three main steps. First, the recorded PMU signal, $y(k)$, is corrected by removing the average value of the data in the data window $(y_{\rm avg})$. The corrected signal $[y^{-}(k) = y(k) - y_{\rm avg}]$ is then divided into different segments of selected lengths, and linear fittings are derived for the data within each segment. Subsequently, an error for each segment is calculated by deducting this linear fitting from the corrected signal in the respective segment. The root-mean-square error of each segment is then used as an indicator to identify an occurrence of a dynamic event in the network. The approximate location of the dynamic event is determined by comparing the root-mean-square errors among different PMU measurements.

B. Data Mining in Large Databases

It is not feasible to apply traditional data mining techniques, such as classification, clustering, regression, prediction, and tracking patterns, to synchrophasor database systems containing billions of data points. Therefore, additional big data analytics tools have been developed to make data mining in large-database systems more effective with traditional techniques. These methods include parallel processing algorithms, such as ordinary least squares, conjugate gradient, and Mann–Whitney U testing [116]. In addition, big data researchers have developed synchrophasor data processing frameworks that can more effectively handle billions of data points [117]. For example, Andersen *et al.* [117] proposed a data processing and storage framework for clustering of micro-PMUs (μPMUs), where the data streams received from μPMUs are time aligned and feed into feature extraction algorithms (e.g., ROCOF, angle difference, etc.) known as “distillers” and stored in the Berkeley Tree Database. This architecture allows redundancy in multiple interdependent data streams, as it only stores the difference between the primary and other data streams.

Among the big data analytics techniques applied to synchrophasor databases, data mining is the most commonly used. Data mining has been applied to synchrophasor measurements for power system dynamic stability assessment (DSA) [118], instability prediction [119], state estimation [120], and protection [121]. Among the data mining approaches, classification approaches are most commonly used for synchrophasor data streams [118]. Regression analysis is another big data analysis technique reported in the literature for synchrophasor data streams.

C. Advanced Statistics

Various statistical indices have been developed for synchrophasor data to predict stability issues in power networks [122], [123]. Ghanavati *et al.* [122] used the statistical indices of autocorrelation and variance on bus voltage measurements to produce early warnings under transient conditions. Linear eigenvalue statistics (LESs) were proposed for synchrophasor data matrices in [123] for situational awareness in power grids. The LESs enable anomaly detection from synchrophasor data streams more efficiently than conventional methods.

D. Scale-Up and Parallel Processing

The conventional algorithms cannot cope with the increasing dimensions of the data and large number of parallel data streams from synchrophasor devices, and hence existing algorithms have been enhanced to deal with large dimensions. To deal with these high-dimensional and parallel data streams, the efficient approach is to decompose the data into low-rank and low-variation components, exploiting the sparsity property of matrices, etc. MapReduce programming models [124], such as Hadoop [125] and Spark [126], are some example techniques. The research study presented in [127] applies parallel DFA to detect transient events from the synchrophasor data using the Hadoop MapReduce model. In this approach, the synchrophasor data are split into a number of data blocks, and each data block is processed in parallel as a map task to determine the fluctuation values. In the final stage, all fluctuation values are combined and compared against a threshold value to identify transient events.

VIII. Recommendations for Future Research

The above review revealed that the transition from model-based oscillatory stability analysis to data-based oscillatory stability analysis enabled by WAMS and big data analytics techniques has provided an effective solution to tackle the critical threats and challenges brought about by the large-scale integration of RESs to system operational planning. More research efforts should be devoted to facilitating this transition, and following research studies are recommended.

1) As existing data-based methods were mainly developed to solve conventional oscillation problems, more systematic research should be implemented to design data-based methods for the emerging or mixed oscillation issues caused by massive RES PECs.
2) There is a great need to develop a breakthrough theory for oscillatory stability monitoring and analysis based on energy flow tracking that can link system-level assessment with device-level tracking and provide a clear physical explanation of the oscillation mechanism.
3) Data quality and cyber security issues must be considered to make existing data-based oscillation monitoring and

analysis tools more practical and reliable. Communication problems, such as data dropout and delay (or lack of data sources) and bad data (or data attack), should be examined.

4) Subsynchronous oscillations play a key role in system stability due to added PEC-interfaced generation. The locations of the measurements and the network topology can significantly impact the observability, which is significant when implementing a synchrophasor-based oscillation monitoring algorithm. Therefore, it is important to investigate the observability of subsynchronous oscillations due to added PEC-interfaced renewables.
5) Big data analytics is an emerging research area in synchrophasor networks because synchrophasor measurement systems accumulate trillions of data points each year. However, only limited research has used these data analytics techniques for oscillatory stability monitoring and analysis, and hence further studies are required to investigate the application of data analytics for oscillation monitoring and analysis.

IX. Conclusion

This article reviewed the state-of-the-art with respect to oscillatory stability monitoring, analysis, and control techniques using synchrophasor technology while placing special emphasis on oscillations induced by PEC-interfaced renewable generation. Many oscillation analysis algorithms were reported in the literature and most can be applied to monitor and analyze different types of oscillations. However, each algorithm must be appropriately tuned based on the characteristics of each oscillation type. Emerging oscillatory stability issues due to PEC-interfaced renewables have yet to be fully explored by the power system community; synchrophasor technology can be used as an effective tool to fully analyze and characterize these oscillations. Big data analytics must be used in the future for oscillatory stability monitoring, analysis, and control because these techniques can reduce the computational burden and improve the latency in processing synchrophasor data streams. Future research is needed to advance oscillatory stability monitoring using synchrophasor data streams, in particular to use these techniques to mitigate PEC-interfaced oscillations.

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