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TOPICAL REVIEW

A Survey of Oscillation Localization Techniques in Power Systems

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ABSTRACT With the increasingly high penetration of renewable energy sources and the more integration of flexible loads, the power system is currently experiencing significant changes. While these changes aim to meet the growing needs of modern society, they also lead to the occurrence of more and more power oscillation events. These oscillations could be harmful to the operation of the power system, even causing power outages in poorly damped power systems. Hence, it is important to locate the source of these oscillations in the complicated power system, as control strategies or actions can be taken to mitigate them. To locate the source of oscillations accurately, many efficient techniques for oscillation source localization have been developed in the past decade using different physical properties of the power system and different methods. This survey focuses on these techniques to localize the source of oscillation in power systems. They can be categorized according to the physical metrics used, such as energy, mode shape, traveling wave, and damping torque. They can also be classified according to the specific methods used, such as data-driven, machine/deep learning, and transforms. The principles of these techniques, as well as their advantages and disadvantages, are discussed. Based on this survey, future research challenges on oscillation localization are outlined. The survey aims to provide a comprehensive review of the most existing techniques for oscillation source localization in the literature so that researchers and engineers can identify the most appropriate technique for their respective domains and applications.

INDEX TERMS Forced oscillation, oscillation source location, phasor measurement unit, sustained oscillation, wide-area measurement system.

I. INTRODUCTION

With the rapid development of smart grid and the wide deployment of renewable energy generation, energy storage, and plug-in electric vehicles, significant changes are being introduced into the existing power systems. These changes may lead to instability in power systems [1]. Instability may manifest as sustained oscillations. Damped oscillation is a normal phenomenon for a disturbed system to go back to its stable operating point, but sustained oscillation is often harmful to the power system and it could happen in reality for various reasons, including improper operating conditions, periodic external disturbances, and malfunctioning controllers. Most sustained oscillations can be categorized into two main types [2]: 1) natural oscillations that arise from ambient variations in generation/loads or impulsive stimulation to the grid (e.g., a line failure); 2) forced oscillations that are caused by persistent electromechanical drivers (e.g., anomalies in governors or other generator controls, equipment-related abnormalities in wind farms). Both can be precursors to equipment or system failures, especially if they cause persistent transfer of a significant amount of power across a wide area. Such unexpected sustained oscillation may reduce the capability of power transfer, result in detrimental consequences on the system equipment, or even lead to a power blackout. For example, in October 2009 in Texas, a direct interconnection of a Type 3 wind farm with a series compensated 345kV transmission

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line led to forced oscillation of about 20 Hz, where currents and voltages exceeded 300% of their normal values, causing severe damage to the wind turbines and the series capacitors of the transmission line in the area [3].

Since sustained oscillation imposes a great risk to the power system with instability, it is crucial to detect, localize, and mitigate them as soon as they occur. The detection allows us to distinguish the type and mode of the power oscillations; the localization allows us to track the source of the concerned oscillation; while the mitigation involves taking measures to remove oscillation and restore stability to the system. Among them, the localization of the oscillation source is invoked when the oscillation is detected, and it is usually a prerequisite for any mitigation actions, as the elimination of the oscillation source is always the most straightforward and effective way to fix the problem. Thus, it is important to develop technologies to localize the source of oscillation as soon and as accurately as possible for system stability.

On the other hand, synchrophasor technologies have come into wide use in recent years due to the requirements for smart grid operations. These technologies use monitoring devices, such as phasor measurement units (PMUs), to take high-speed measurements or samples of the phase angle, voltage, and frequency at different locations in the power systems that are time-stamped with high-precision clocks. The phasors measured on an interconnected power grid require a shared timing reference, typically provided by a synchronizing source. This source signal should be referenced to coordinate the universal time to ensure uniformity across the system. The Global Positioning System (GPS) is a satellite-based system that can serve as the main synchronization source and offer a time reference for communication networks.

Synchrophasor technologies have been widely used in a number of applications, such as real-time wide-area monitoring [4] and generator model validation [5]. Due to their convenience and availability, synchrophasor technologies have also been widely used for characterizing oscillations, including the detection of natural and forced oscillations, the calculation of damping, the estimation of modes and mode shapes, and the localization of oscillation source [6], [7]. Thus, there is an increasing trend in power system engineering to use PMU and other synchrophasor technologies for the localization of the source of oscillation.

In general, oscillation source localization techniques can be classified as model-based, measurement-based, or hybrid. Model-based techniques rely on pre-assumed models of the power system to locate the source of oscillation. This is its advantage because such models may describe the physical mechanism of the system to reveal the root cause of oscillations. However, due to the complexity of practical power systems, these models may not be accurate in certain places or at certain times, leading to large localization errors. Measurement-based techniques are model-free and can be adapted to different network topologies, components in power grids, and sources of oscillations, as they do not rely on any pre-assumed models. In practice, they may also be free of additional equipment. Robust against measurement noise, time delays, missing data, and even cyber-attacks should also be considered. However, to find the real-time location of the oscillation source in modern power systems with high accuracy, the computational burden and efficiency of these techniques are often a concern. Alternatively, these two techniques can be combined by using the difference between the models for localization at the first time and then measurements for localization as a reference in hybrid techniques. Nevertheless, many other methods for oscillation source localization in the current literature do not fall into these three categories. Hence, a more comprehensive review of different oscillation localization techniques is required.

This work will survey the principles, advantages, and disadvantages of existing oscillation source localization techniques available in the literature. To achieve this, first, several basic concepts on power system oscillation will be explained in Section II. Section II will also present several important metrics widely used in existing oscillation source localization techniques. In Section III, different techniques for oscillation source localization will be reviewed. To present them more clearly, firstly, these techniques will be categorized according to the different metrics they use, including energy, damping torque, mode shape, traveling wave, and oscillation power and impedance. Secondly, they will be categorized according to the specific methods used, including data-driven methods, reference-based methods, machine/deep learning methods, and transform-based methods. Section IV will outline future challenges for oscillation source localization following the discussion in Section III. Finally, Section V will conclude the work.

II. BASIC CONCEPTS AND IMPORTANT METRICS

A. POWER SYSTEM OSCILLATION

The oscillation frequency in contemporary power systems spans from less than one Hz to hundreds of Hz. In the early era of power system development, power oscillations were rare because most generators were closely connected to loads. However, nowadays the large and widespread demand for electricity requires the transmission of a huge amount of power over a long distance, giving rise to more power oscillations. Power system oscillations can be triggered by a variety of factors, such as variations in load and renewable energy generation, torsional resonance, and converter control system switching. As mentioned before, power oscillation can be categorized into natural oscillation and forced oscillation. Natural oscillation arises from ambient variations in generation/loads or impulsive stimulation to the grid, such as line failures. Forced oscillation can be caused by an external periodic disturbance or mis-tuned generator controllers, often with persistent electromechanical drivers such as anomalies in governors or other generator controls, and equipment-related abnormalities in wind farms. The forced oscillation can be sinusoid, limit cycles, pulse trains, etc. Fig. 1 summarizes different power oscillations and their possible causes.

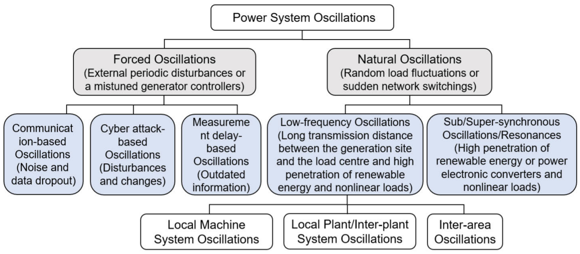

FIGURE 1. Classification of power system oscillations.

The oscillation can be described by the linearized power system model through the following equation

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)$$
$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) \tag{1}$$

where $\mathbf{A}$ is the state matrix, $\mathbf{B}$ is the input matrix, $\mathbf{C}$ is the output matrix, $\mathbf{x}(t)$ is the state of the power system, $\mathbf{y}(t)$ is the output of the power system, and $\mathbf{u}(t)$ is the input or the forced oscillation of the system.

1) COMMUNICATION ISSUES/CYBER-ATTACK/MEASUREMENT DELAYS

Communication issues will affect the power system performance, particularly in complicated scenarios the require network control, operations, and data transmission. For example, data loss, noise, interference, latency are some major communication issues that could occur in data exchange. These issues could introduce disturbances that lead to forced oscillations in a system. Also, cyber-attacks on power systems have become a serious concern as these infrastructures become increasingly digitized and interconnected. These malicious actions can affect the system behavior by introducing disturbances or changes. Additionally, measurement delays in receiving feedback can lead to adjustments in the control system that are based on outdated information, producing oscillations that otherwise would not occur if the system can have timely measurements to respond to its real-time conditions.

2) LOW-FREQUENCY OSCILLATION (LFO)

Power oscillation in large interconnected systems often manifests LFO. This is often caused by mechanical oscillation of the rotor phase angle concerning a rotating frame and typically ranging between 0.1 and 3.0 Hz [8]. It can be divided into three categories: 1) local machine system oscillation linked to one synchronous generator or a small group of coherent synchronous generators within a single plant against the load center (0.7 to 3.0 Hz); 2) local plant/inter-plant oscillation with two or more synchronous generators in the same power plant or nearby power plant against one another (0.7 to 3.0 Hz); 3) inter-area oscillations with a group of coherent synchronous generators in one area against another group of coherent synchronous generators located in another area in a wide-area power system (0.1 to 0.7 Hz) [8], [9], [10], [11].

3) SUB/SUPER-SYNCHRONOUS OSCILLATION/RESONANCE (SSO/SSR)

In contrast to LFO, SSO/SSR has a wide range of oscillatory frequencies due to a variety of causes. They are often classified based on the participating equipment. Recently, owing to the increasing integration of converter-interfaced equipment, such as wind and solar power generation, more and more types of SSO/SSR are being observed [11], leading to the following types. SSO/SSR can be generally divided into three categories: 1) SSR between rotating components and a series compensated grid (induction generator/machine effect (IGE/IME), torque amplification (TA), and torsional interaction (TI)); 2) control device dependent SSO (steam/hydro turbine against fast response controllers and so-called sub-synchronous torsional interaction (SSTI)); 3) sub-synchronous control interaction (SSCI) among power electronic converters (PECs) and series compensated grids.

In steady states, both natural and forced oscillations show sustained oscillations with nearly constant amplitude. The intrinsic system damping for natural oscillation is zero or negative. In contrast to natural oscillation, the intrinsic system damping for forced oscillation is positive. Thus, if the forced oscillation occurs at a frequency close to a poorly damped system mode, it can also have a resonance effect which can deteriorate the power oscillations in the system. Oscillation mode has rich information on the stability of power systems.

Forced oscillation may render inaccurate estimation of the natural oscillation mode and mode shapes. To improve the power system's stability, reliability, and resilience, it is important to estimate or determine the mode of oscillation or distinguish between natural oscillation and forced oscillation, before any action can be taken.

B. OSCILLATION ESTIMATION

Synchronous power systems are inherently multi-modal and under-damped due to electromechanical physics. Oscillation mode frequency, mode damping factor, and mode shape are three key parameters that describe the properties of the oscillation or determine the types of the oscillation. The mode frequency is the frequency of a certain mode oscillation. The mode damping factor is a measure of how long it takes for a certain mode to dissipate in transient. The mode shape is a complex number associated with a certain mode and the system state such as generator rotor speed. The oscillation estimation methods focus on estimating the oscillation modes of the power system, which can be classified as model-based and measurement-based methods [12].

Model-based methods use system models or device parameters for estimation. They can be categorized as non-linear methods and linear methods [13]. Nonlinear methods encompass approaches, such as time-domain simulation and normal form analysis, which are commonly regarded as standard nonlinear methods for offline analysis of oscillation [14]. These methods require the solution to the differential-algebraic equations that represent the power system model via numerical techniques to obtain time responses of variables or theoretically analyze whether the power system states converge to a stable operating point or not [13], [15].

They offer several advantages, such as the ability to investigate system dynamics under various modes, detecting characteristic patterns for complex phenomena, and involving the nonlinear behaviors of other controllers concurrently. They also have disadvantages. For example, the normal form analysis generally requires advanced nonlinear system theory on a simplified model, as it cannot deal with a complicated power system model. The time-domain simulation may not trigger all oscillation modes so it can be challenging to determine the oscillation type solely based on limited time-domain responses. Furthermore, time-domain simulation models rely on detailed parameters of all elements, which may not be accurately obtained due to proprietary constraints from manufacturers. Longer simulation time and heavy computation workloads also make their online applications difficult.

On the other hand, linear methods, such as eigenvalue analysis, extract the oscillatory modes through the eigenvalue analysis by linearizing the dynamic model of a power system at a certain operating point [16], [17]. They are capable of calculating the corresponding controllability, observability, and participation factors for all generators [16]. However, the system may operate at a state far away from the operating point where the system is linearized, which is often the case following the disturbance of sporadic faults. In this case, the linearized model may not correctly reflect the dynamic behavior of the system. Such "once-and-for-all" linearization methods are not suitable for power system stability monitoring [18]. For example, the eigenvalue analysis used by the utility companies failed to identify the unstable oscillation mode of the 1996 outage in the USA [19], [20].

Realizing the limitations of model-based methods, the use of operating data to identify the oscillation mode has come to light in recent years. The measurement-based methods can extract the electromechanical oscillatory modes and damp from the measurement [12], [21]. Advanced measurement and communication techniques, such as PMUs and wide area measurement systems (WAMSs), have been developed to facilitate measurement-based power system oscillation mode extraction, stability monitoring, and the implementation of control strategies. Deployment of PMUs with a high sampling rate has enhanced the observability of the power system and has become a significant technological contributor to measurement-based approaches [21].

One appealing feature of measurement-based approaches is that they do not require any detailed power system models or accurate parameters [12]. Moreover, with the real-time measurement from WAMS, the result from such approaches can represent the actual dynamic features of the system [12]. These methods use three different types of measurements: probing data, ambient data, and ringdown data [22], [23].

The probing-data-based method estimates the parameters of the dominant modes from the responses incurred by manually injecting low-amplitude pseudo noise, such as step signal, pulse signal, or color noise, into the original system [22], [23]. The ambient-data-based methods extract the electromechanical oscillation from the ambient data excited by the power system operating at an equilibrium point with small amplitude random demand and generation fluctuation, i.e. small disturbances [22], [23]. The ringdown-data-based method uses ringdown data from major disturbances such as line tripping, and generator disconnecting to extract the electromechanical modes.

Since ringdown and ambient data contain disturbance from daily grid operations, whereas probing data are triggered by intentional injection, the electromechanical modes are mostly estimated from ringdown data and ambient data [23]. Also, compared with ambient data, ringdown data are much easier to collect and can provide rich information on LFO modes, because they can be measured during large system disturbances, such as line trip and generation trip [22].

The estimation of frequency and damping factor can be achieved using several methods, such as the Prony method in [24], matrix pencil method in [25], and Kalman filter methods in [26]. The Prony method is based on the assumption that a discrete series of measured values of any sinusoidal or exponentially damped signal can be approximated by a linear combination of exponential terms. The matrix pencil method formulates the ringdown analysis problem as a generalized eigenvalue problem of an associated matrix pencil. The Kalman method is a recursive algorithm for optimal estimation of linear stochastic processes, which is sensitive to initial values.

C. OSCILLATION MITIGATION

Oscillation mitigation often requires additional controls to provide enough damping or merely remove the oscillation source. In current practices, WAMS has been proven successful in monitoring and analyzing the dynamics of power systems. For example, low-frequency oscillation monitoring and mitigation based on wide-area measurement signals have been effectively implemented in networks such as the European interconnected network [27], the State Grid of China [28], and the North American grid [29]. The wide-area information provided by WAMS holds significant potential for use in various control devices (e.g., power system stabilizers (PSSs), high voltage direct current (HVDC), and flexible AC transmission systems (FACTS)) to formulate wide-area control strategies for the overall stability in large power systems. By selecting optimal damping signals on a global level rather than locally, the wide-area controller has the potential to achieve more effective performance [30],

[31]. Currently, in China Southern Grid, wide-area stability control is being considered as supplementary control for multi-terminal HVDC transmission systems to dampen inter-area oscillation within interconnected systems. Local measurement-based PSS and wide-area damping control (WADC) are typical oscillation damping controllers that can be added to the generator's excitation systems [32], FACTS devices [33] or HVDC links [34] to provide supplementary damping and suppress LFOs.

Local-measurement based PSS furnishes an electromagnetic torque to the generator, which can be decomposed into a synchronizing torque component aligned with the rotor angle deviation and a damping torque component correlated with the speed deviation [35], [36], to supply damping torque to the generator rotor oscillation, utilizing rotor speed deviation as feedback [21].

Deploying PSSs at generators with local feedback signals remains a conventional strategy for enhancing the small-signal stability of a system. It is effective in tackling local area oscillations. However, PSSs are relatively less effective in damping inter-area oscillation modes, due to the limited observability and controllability of the inter-area mode from local measurements [32]. Unfortunately, inter-area LFOs with inadequate damping are increasingly prevalent amidst rising power demand at load centers and increased penetration of renewable energy sources [37]. This calls for advanced controllers to provide adequate damping to inter-area mode. In this regard, lead-lag-based WADCs leveraging remote measurements from WAMS have garnered significant attention [18], [38], [39], [40], as in Fig. 2. As depicted in this figure, remote measurements can be gathered by PMUs and transmitted through the WAMS to actuators like generators, FACTS, and HVDC systems. Within this setup, WADCs offer supplementary control to suppress inter-area LFO.

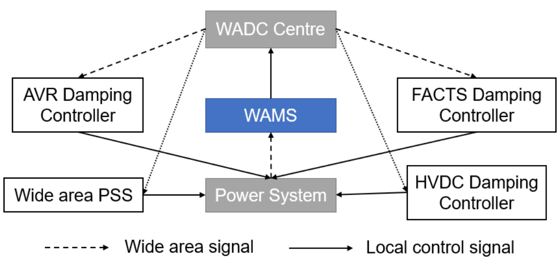

FIGURE 2. **Basic framework of wide-area damping control [13].**

D. OSCILLATION SOURCE LOCALIZATION AND IMPORTANT METRICS

Oscillation source localization is generally performed after the oscillation mode and type are identified, and it provides targets for subsequent mitigation actions. However, it is quite challenging to locate the real disturbance source due to the complexity of a power system. Many methods have been developed in the past decade. These methods often use some important metrics of the power system to localize the disturbance source.

1) DISSIPATING ENERGY FLOW

The occurrence of the forced oscillation is often followed by the propagation of the oscillation energy in the power system. Therefore, the dissipating energy flow (DEF) method can be applied to trace the source of forced oscillation by identifying the direction of the energy propagation. Generally, the DEF from bus i to bus j through branch L_{ij} is defined as [41]

$$\begin{aligned} W_{ij}^D &= \int (\Delta P_{ij} d\Delta\theta_i + \Delta Q_{ij} d(\Delta \ln U_i)) \\ &= \int (\Delta P_{ij} 2\pi d\Delta f_i dt + \Delta Q_{ij} d(\Delta \ln U_i)) \end{aligned} \tag{2}$$

where P_{ij} and Q_{ij} are the active and reactive power flow deviations on branch L_{ij}, respectively, Δ represents the deviation from a steady-state value, $\Delta\theta_i$ and Δf_i are the deviations of bus voltage angle and frequency at bus i, respectively, $\Delta \ln U_i$ is the logarithmic deviation of the voltage magnitude at bus i.

An energy flow is expressed by (2) based on the assumptions of lossless networks and constant power load models. The DEF method in [41] locates the source of oscillation by extracting the data from the slope of (2) at varying amplitude of oscillations with a realistic model of generators. The device producing dissipation energy (increasing W_{ij}^D) is the source. The incremental energies (IEs) of the IEEE benchmark 2-area 4-machine and New England 10-machine 39-bus power systems are shown in Fig. 3 and Fig. 4, respectively. In Fig. 3, G2, L7, and L9 are detected as the FO sources due to their positive IEs. In Fig. 4, G7 and G8 are identified as the FO sources due to their positive IEs. This method is based on strong assumptions of lossless networks and constant power load models.

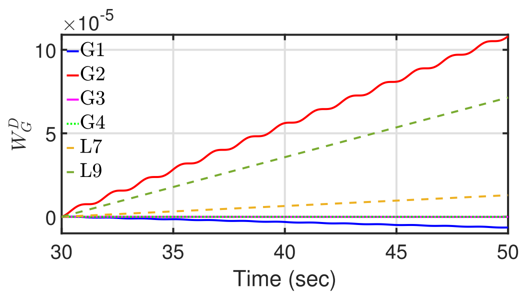

FIGURE 3. **IEs of generators for forced oscillation frequency $f = 0.66$ Hz in the 2-area 4-machine system.**

2) MODE SHAPE

Mode shape is represented by the relative magnitude and phase of the oscillation mode. They can be calculated from the right eigenvectors of the state matrix of the linearized power system model. The eigenvalues of a matrix are given by the values of the scalar parameter λ for which there exist

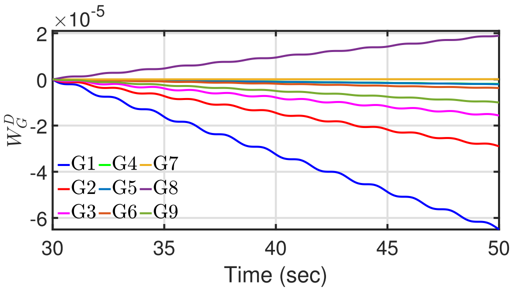

FIGURE 4. IEs of generators for forced oscillation frequency $f = 0.6$ Hz (zoom in G1-G9) in the 10-machine 39-bus system.

non-trivial solutions to the equation

$$\mathbf{A}\Phi_\mathbf{i} = \lambda_i \Phi_\mathbf{i} \tag{3}$$

where $i = 1, 2, \cdots, n$ index the eigenvalues, $\mathbf{A}$ is the state matrix of the power system (a $n \times n$ matrix) in (1), $\Phi_\mathbf{i}$ is the right eigenvector ($n \times 1$ vector), and λ_i is the i-th eigenvalue.

The oscillation mode λ_i is comprised of oscillation frequency f_i and damping factor σ_i with

$$\lambda_i = \sigma_i \pm j2\pi f_i \tag{4}$$

The largest relative magnitude, the most leading phase of the mode shape (small or negative damping), or their combinations may represent the source of oscillation. This metric can be used for multi-mode oscillations. Mode shape magnitude is not dominant in the resonant case when the forced oscillation frequency is close to the natural oscillation in the power system. This imposes challenges to methods using mode shape [42].

3) DAMPING TORQUE

The electromagnetic torque variation ΔT_e is defined as [43]

$$\Delta T_e = K_s \Delta\delta + K_d \Delta\omega \tag{5}$$

where K_s and K_d are the synchronizing and damping torque coefficients, respectively, $\Delta\delta$ and $\Delta\omega$ are the variations of rotor angular and speed, respectively. It can be observed from (5) that the synchronizing component is proportional to the variation of angular $\Delta\delta$, and the damping component is proportional to the variation of speed $\Delta\omega$. Using damping torque, the damping torque for each generator is estimated at the dominated mode first, and then the generator with a negative damping torque coefficient K_d is considered as the source.

4) TRAVELING WAVE

The principle of electromechanical wave propagation can be applied to locate the oscillation source in the traveling wave method. In general, the distance equals the product of velocity and time. Assume that the electromechanical wave generated by oscillation travels through the electric grid as a continuum, one has

$$(x_i - x_0)^2 + (y_i - y_0)^2 = v^2(t_i - t_0)^2 \tag{6}$$

where (x_0, y_0) is the location of oscillation, t_0 is the time the oscillation starts, (x_i, y_i) is the location of the measurement and t_i is the time of measurement, for $i = 1, 2, \cdots, I$, and v is the speed. By using locations and times of measurements, the location and the time of the oscillation can be determined.

Only the first few periods of the wave in the measurements are required to determine the arrival time or time difference between different locations in traveling wave-based methods [1]. Therefore, the traveling wave-based method has a shorter processing time than other methods. However, a highly accurate arrival time of the traveling wave is required from PMU, but this may be challenging due to the impact of the non-constant wave speed in the network and the independence of different network topologies in real applications [44]. Fourier transform, fast Fourier transform, and wavelet transform may be employed for signal processing of high-frequency non-stationary traveling wave signals [44].

In summary, this section has discussed several basic concepts and definitions of power system oscillation, as well as important metrics that have been widely used in existing oscillation source localization methods. In the next section, different localization methods for oscillation sources will be surveyed. Note that this survey is mainly for localization at the generator level. There are also works on localization at the device level, such as [45] and [46] but these are beyond the scope of the work. Note also that there are a few works in non-English databases but due to the difficulty in accessing these databases, they are not included in this survey. Hence, some of these works were reviewed in [1] but not here. Finally, [1] is another survey on oscillation localization in the literature. Compared with [1], our survey is more comprehensive by including techniques developed after 2017 as well as works before 2017 that are not included in [1]. Also, our survey provides a more detailed discussion than [1]. For example, the learning-based techniques have seen great development in recent years due to the advances in artificial intelligence but these techniques were only discussed very lightly in [1].

Next, we will discuss the localization of the oscillation source based on metrics in Section III and methods in Section IV, as summarized in Fig. 5.

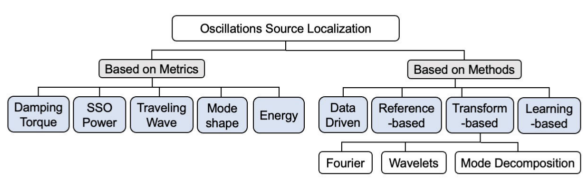

FIGURE 5. Localization of the oscillation source.

III. OSCILLATION SOURCE LOCALIZATION BASED ON METRICS

In this section, different localization techniques for the source of oscillation in a power system will be reviewed. These oscillations could be natural oscillations, such as LFO and

SSO, or forced oscillations. The review will first categorize the techniques based on the physical metrics they use in this section. Then, it will categorize them based on the specific methods they adopt in the next section. Note that these two categories are not exclusive to each other. For example, a machine learning based method could use the energy or the damping torque as input features. Similarly, a damping torque technique could adopt the data-driven method discussed for data processing.

A. DAMPING TORQUE

The damping torque technique is one of the earliest techniques developed for source localization. It localizes the source of oscillation by considering the system damping using the damping torque coefficients or other related parameters of each generator in the power systems. The generator with negative damping is often treated as the source of oscillation.

In [47], for a multi-converter system, the admittance model of the system was derived. The weakly oscillatory modes were calculated as the zeros of the determinant of the nodal admittance matrix (NAM). Their modal power was calculated for each converter. The real part of the modal power reflects the participation of the admittance of the converter on the system damping and a positive real part yields positive damping. Then, the converter with significantly larger modal power than others was considered as the source of oscillation.

In [48], the forced oscillation in a two-machine system was analyzed. Based on this analysis, the generator electromagnetic torque was obtained as $\Delta T = K_s \Delta\delta + K_d \Delta\omega$, where K_s is the synchronous torque coefficient, K_d is the damping torque coefficient, $\Delta\delta$ is the power angle change, and $\Delta\omega$ is the angular velocity change. A new Prony analysis was proposed to obtain these values from the data. Then, the damping torque was calculated using this equation. The machine providing negative damping to the system was identified as the source of oscillation. The method was simulated in a two-area four-machine system for a low frequency of 0.567 Hz.

In [49], a new concept of oscillation phasor was proposed to characterize the type of sustained oscillation from power plants. Using the phasor, a two-stage scheme was presented to locate the sustained oscillation source. First, Prony analysis and the first wave algorithm were used to calculate the defined oscillation phasor using active power and angular frequency. Then, the phase relationships between the generator that is the source of oscillation and other generators were derived, which was used to find the location of the source and calculate the damping ratio. If this ratio was between 0 and 0.02, the oscillation was considered as weak damping, and otherwise, it was considered as forced oscillation. The proposed scheme was tested on a two-area four-machine system for a low frequency of 0.497 Hz and the generator that has a phase ahead of all other generators was considered as the source of oscillation. It was also tested using real event data on September 16 2013 in China with a frequency of 1.3 Hz due to the incorrect setting of PSS equipment.

In [50], each generator was converted to the inertia of center (COI) coordinate, and their rotor angle and rotor angular velocity in the COI coordinate system were calculated. Then, the generators were grouped into two based on the angular acceleration, and their Pearson correlation coefficients were calculated to identify the source. It was tested in the Henan power network for a low frequency of 1.0055 Hz.

In [51] and [52], to localize the source, each generation bus was assigned a weighting factor calculated using the active power and the angular velocity angle. This required PMU measurements at each generator. Then, three decision functions were constructed using these weights to identify the source of oscillation. The method was validated on the New England 10-machine 39-bus benchmark power system in a Real-Time Digital Simulator and a MATLAB environment.

In summary, most of these methods calculate the damping torque or other parameters related to system damping, e.g. impedance, resistance, and inertia, to identify the source of oscillation. The frequency they deal with is around 1 Hz. It is important to distinguish the forced oscillation from a weakly damped system. Consequently, the damping ratio needs to be calculated. Table 1 summarizes the damping torque techniques discussed above.

B. SSO POWER

Sub-synchronous oscillation (SSO) is becoming increasingly serious in modern power networks due to the high penetration of renewable energies and the frequent use of power electronics. The identification of the source of SSO is complicated due to the complexity of these power systems. SSO power has recently been used for source localization.

In [53], for inverter-based resources (IBRs), the sub-synchronous frequency component of the instantaneous power as sub-synchronous power (SSP) was calculated. First, the equations for the instantaneous power of grid-following IBR and grid-forming IBR were derived. Then, the direct current (DC) components with independent fundamental and sub-synchronous frequency-related elements were separated. From the DC components, the fundamental frequency-related components were filtered out using the amplitude coupling relationship between these components to extract the sub-synchronous frequency-related component or SSP. Finally, the flow direction of SSP was used to locate the oscillation source. The IEEE 39- and 118-bus systems were used to verify the method.

In [54], firstly, a novel circuit law called Kirchhoff's power law (KPL) was proposed based on Kirchhoff's current law. Then, the currents and voltages of branches were used to calculate the active power and reactive power at the oscillating frequency. Then, the path of oscillation propagation was identified using the oscillation power flow direction. The unit with negative impedance or the unit

TABLE 1. Summary of damping torque techniques.

Ref.	Metric	Method	Test
[47]	Modal power	Admittance model	9-converter 39-node system simulation
[48]	Damping torque coefficient	Prony analysis	Two-area four-machine simulation
[49]	Oscillation phasor and damping ratio	Prony analysis and first wave	Two-area four-machine simulation and event data in China
[50]	Rotor angle and rotor angular velocity	Pearson correlation and grouping	IEEE 4 machine 11-bus simulation and Henan network
[51], [52]	Active power and angular velocity angle	Graph theories and decision functions	New England 10-machine 39-bus benchmark system

that only transfers power to the outside was considered as the source. The method was evaluated in an ideal negative resistance circuit and a parallel DC-DC converter system. Both active and reactive power oscillations can be located.

In subsynchronous resonance (SSR), synchrophasor data are dominated by four modes: two from the fundamental frequency and two from the subsynchronous frequency. In [55], a dq0 transform-based method was used to extract the SSP in subsynchronous resonance (SSR) to avoid the interference of the fundamental frequency components on the subsynchronous frequency components. The direction and amount of SSP was then used to locate the source of SSR. Case studies on a doubly fed induction generator (DFIG)-based wind farm connected to the system were also presented.

In [56], synchrophasor data were used to extract the SSO power and impedance using the Prony analysis and the matrix pencil method. Then, using the voltage and current phasors, the resistance for a DFIG structure was calculated and the one with negative resistance was considered as the source. The method was applied to an actual incident with 23 wind farms.

In [57], a Hankel matrix was constructed based on voltage and current measurements from each wind turbine connection port followed by a singular value decomposition. After the noise and interference were removed from singular values to determine the number of oscillation modes, the matrix pencil method was used to extract the modal parameters, such as amplitude and phase, to calculate the SSO power. Then the SSO power was used to determine the location of the oscillation source that has a positive SSO power to transmit power.

In [58], instantaneous values of voltages and currents were obtained from the power measurement system to calculate the oscillation risk indicators based on current fault characteristic values and damping coefficients. Then, a modal power analysis and an amplitude comparison method were used to rank the contribution of different oscillation sources. An AC power export system based on an actual renewable energy grid in the PSCAD/EMTDC platform with an oscillation of 14 Hz and an actual photovoltaic power station that experienced an oscillation of 12 Hz was used to test the method.

In [59], for subsynchronous control interaction (SSCI), three criteria for SSCI source identification were first proposed. One was based on reactive and active power. One was based on impedance with no coupling between SSCI components and the third one was based on impedance with frequency coupling between subsynchronous and complementary supersynchronous components. The SSP flow was calculated and the three criteria were used to identify the source. A case study of the July 2015 SSCI incident in Hami China was used to evaluate the method.

Reference [60] proposed to locate the nonlinear SSO sources using energy supply on port (ESP) and bicoherence. The ESP was calculated using the instantaneous values of measured voltages and currents at ports. The tendency of the ESP indicated the transient energy injection from a certain subsystem into the rest of the network to locate the source. After source localization, the bicoherence coefficient was used to examine the nonlinearity of the oscillation source.

In summary, most of these methods use the SSO power or SSP, They vary in the ways used to calculate the SSP. Also, most of them tackle the SSO with renewable energies. These oscillations often have much higher frequencies than LFO. Table 2 summarizes these methods.

C. TRAVELING WAVE

The traveling wave methods identify the source of oscillation based on the arrival time of the oscillation propagation. The earlier the propagation wave arrives, the closer the unit is to the source of oscillation, as it takes time for the oscillation to propagate through the power network.

In [44], a detailed review of the traveling wave method was provided. In [61], PMU measurements were used to determine the time of arrival of electromechanical waves propagating from the fault point. By taking the speed of electromechanical wave propagation as well as the topology of the network into account, the method was able to detect the faulty line. Then, by adding fictitious buses inside the faulty line and applying a binary search method, the location of the fault was accurately pinpointed. The main advantage of this is the use of a limited number of PMUs which reduces the cost of implementation.

In [62], a novel method of locating the source of forced oscillation was proposed based on a concept called equivalent electrical distance. Firstly, the actual grid nodes were mapped to a complex plane on the basis of equivalent electrical distance theory. Then, PMU nodes were selected according to the defined index of the coupling degree of the generator and load. In the end, the disturbance source was effectively located by solving an optimization problem based on the

TABLE 2. Summary of SSO power techniques.

Ref.	Metric	Method	Cause	Test
[53]	SSP	Power equations, filtering	IBR	IEEE 39- and 118-bus systems
[54]	Active, reactive SSP	Kirchhoff's power law	Active or reactive	Ideal negative resistance circuit and a parallel DC-DC converter system
[55]	SSP	dq0 transform	SSR	Wind farm systems
[56]	SSP and impedance	Prony analysis, matrix pencil	DFIG	Actual incident with 23 wind farms
[57]	SSP	SVD, matrix pencil	DFIG	Three wind-farm grid-connected model
[58]	Modal power	Modal power analysis, amplitude comparison	Wide	Renewable energy grid in PSCAD/EMTDC, actual photovoltaic power station
[59]	Power, impedance	Three criteria	SSCI	SSCI incident in Hami China
[60]	ESP	Bicoherence coefficient	Wind farms	SSCI incident in Hami China

Geiger theory of seismology and the half-plane method. The IEEE 30-bus system was used to verify the validity and accuracy of this locating method.

In summary, the traveling wave method often requires the topology of the network in order to calculate the arrival times and then pinpoint the source. They rely on the principle of electromechanical wave propagation to locate the oscillation source. Thus, accurate calculations of the arrival time of the oscillation at PMUs and the network map are important. These methods can not only be used for oscillation localization but also for any fault localization. Furthermore, these methods have fast detection capability, which has tremendous potential for oscillation source localization in future power systems.

D. MODE SHAPE

Mode shape refers to the relative magnitude and phase of the oscillating component in the system. It can be calculated by using the right eigenvectors of the state matrix $\mathbf{A}$ of the linearized system model in (1). This method is efficient when the system model is accurate but this is often difficult in practice. A good review of these techniques can be found in [63].

In [64], the oscillation mode angle was used without the system topology information to locate the source of oscillation upon detection. Fourier transform was applied to extract the frequency and mode angle of the oscillating component. The oscillation mode angle is the angle of the oscillating phasor at a certain time. The source area of the forced oscillation usually has the most leading oscillation mode angle than other areas, and the oscillation mode angle gradually decreases in the adjacent areas. Thus, by comparing the measured mode angles, the source area can be identified. The proposed algorithm was validated using the January 2019 forced oscillation event in the Eastern Interconnection of North America at 0.25 Hz.

In [65], the angle and speed measurements at the generators were used to estimate the phase, magnitude, and frequency of the forced oscillation. Then, the estimated values were used in a system of equations based on the characteristics of the analytical response of a linear system to an external input, along with the eigenvalues and eigenvector of the system state matrix, to calculate a vector whose largest value indicates the location of the source. This was tested using the 16 machine 68 bus system at 1.5 Hz.

In [66] and [67], for a system with multiple oscillation sources, a new localization method was proposed. Firstly, based on the multi-source oscillation model, the expressions of voltage and current in this case were derived. Then, using the definition of oscillation center, the oscillation center position function was constructed to describe the position of the oscillation center for positioning. This method relies heavily on the expressions or the models of voltage and current.

In [68], variational mode decomposition (VMD) was applied to extract and determine the relative phase shift, which was then used to identify the source of oscillation in the power system network. The method was tested using the two-area system and PMU data from Power System Operation Corporation (POSOCO) Limited in India.

In [69], a combined method for forced oscillation source location using synchrophasor measurements was proposed by localizing the source using dissipating potential, oscillation magnitude, and oscillation mode angle to reach a final decision based on the weights of the three methods. A forced oscillation localization tool was developed without knowing the system topology information.

In [70], the effect of the location of the forced oscillation source on the inter-area electromechanical mode resonance was studied via simulation over a simple two-generator system and the full Nordic power system simulation model. It was reported that as the forced oscillation moves away from "the centre of the inter-area oscillation mode" towards the ends of the system, the amplification effect of forced oscillation increases approximately linearly with the electrical distance measured by the voltage angle difference. This can be used to localize the source of forced oscillation. Similarly, in [71], a new method was proposed to locate the source of disturbance based on the space-time characteristics of low-frequency oscillation using the angle difference of voltage phasors between both sides of the oscillation center. This works for both low-frequency and out-of-step oscillations.

In [72], a method using the relationship between the phase of oscillations and the relative damping contribution was proposed. The method was based on detecting differences in the damping contribution from different generators. These differences can be seen from the phase of oscillation at different parts of the system. Generators with a leading phase provide less damping to the mode, while generators with a lagging phase provide more damping. The generator with the least defined damping contribution is considered as the source. A small number of voltage phasor measurements covering the whole system was sufficient to identify the region containing the source. The method was tried for a real event in ISO New England at a frequency of 0.9 Hz with 39 PMUs.

In [73], the harmonics at sufficiently high frequencies were studied and shown to degrade much more quickly with the spatial distance from the oscillation source than that at the fundamental frequency. Based on these observations, the ratio of the amplitude of the harmonics to the amplitude of the fundamental frequency was proposed to localize the source that has the highest ratio. The method was tested and verified in the oscillation event in ISO New England (ISO-NE) on July 20, 2017 at a frequency of 1.13 Hz, in the Eastern Interconnection on January 11, 2019 at 0.25 Hz, and in the Western Interconnection at 1.14 Hz.

In [74], a new method was proposed by comparing the oscillation mode shape of the forced oscillation with that of the natural oscillation that the forced oscillation resonates with. The oscillation source was determined as the location that has the largest angle difference between the forced oscillation mode and the natural oscillation mode. This idea is similar to [70] and [71]. The method was tested in two incidents in the U.S. Eastern Interconnection system in Florida in 2019 at 0.25 Hz and in Georgia in 2016 at 0.7 Hz.

Reference [75] proposed a method to locate the source of oscillation source by building transfer functions between bus frequencies using PMU data, and the relative location of the oscillation source with respect to measurement points was determined by using the magnitude responses and phase responses of transfer functions. This is similar to the electrical distance method, except in the frequency domain.

In [76], frequency domain decomposition (FDD) was used to extract the low-frequency oscillation modes from PMU measurements. The damping ratio, modal frequency, and the mode shape of poorly damped oscillatory modes were calculated. Then, the Pearson correlation coefficient was used to identify the source of the oscillation mode with high correlations.

Reference [77] took advantage of time-stamped waveform measurements that were typically available on the terminals of series compensated transmission lines to calculate the frequency, current magnitude, and damping of SSR. Based on the values of these parameters, proper actions were taken. It was simulated in a circuit with a DFIG-based wind farm connected to the grid through a series compensated line of 200 km.

In summary, the mode shape techniques can use models, such as [65], [66], [67], and [75], or measurements, such as [64], [68], and [76], to obtain the mode shape for localization. The techniques using data and transforms will be discussed in more detail in the next subsection. Some also rely on the relationship between forced oscillation and natural oscillation, such as [70], [71], and [74]. Most of them deal with one source but [66] and [67] consider multiple sources. Table 3 summarizes the mode shape techniques.

E. ENERGY

The energy technique is probably one of the most widely used oscillation source localization techniques in the literature. It calculates the dissipating energy flow caused by oscillation and then traces the flow back to the component that produces energy as the source of oscillation. This technique has many advantages, such as simplicity and high accuracy. However, the efficiency of this technique also relies on some strong assumptions, such as lossless networks and constant power loads. Moreover, it requires a large number of PMUs, and in wideband oscillation, the technique may fail as the energy flow changes with frequency [6].

1) EARLY WORKS

The earliest works on the energy technique are perhaps [78] and [79]. In [78], for a simple two-machine system, the inter-area oscillation was characterized by studying the periodic interchange of energy between two groups. The group producing the energy exchange was identified by using the phase of the coefficient of the dominant energy mode in the kinetic energy for each generator. In [79], the energy flow and peak instantaneous power were calculated from voltage and current measurements to determine which side of a recording device has disturbance. This can be extended to localize the source of oscillation by using multiple recording devices.

The use of the techniques in [78] and [79] in a practical network requires a large number of measurement units, which was not possible at that time. Hence, the energy technique did not receive much attention until after more than a decade when more monitoring devices started to be deployed.

In [41], a new energy technique was proposed. First, the consistency of energy dissipation with the damping torque of a generator was proved so that the component producing energy has negative damping and was considered as the source. Then, energy functions were constructed to compute energy flow at each bus in the network, from which the energy dissipation or production of a component was obtained to identify the oscillation source. This paper lays the theoretical foundation for most energy techniques developed later. Similarly, in [80], forced oscillation caused by the continuous cyclical load disturbances in a single-machine infinite-bus system was localized by analyzing the difference in the energy conversion characteristics between the forced oscillation and weak damping and using energy functions with the linear equations of motion of the rotor.

In [81], by calculating the energy supply injected into the network at each port using the port-controlled Hamiltonian theory, the oscillation source was located. This method was decentralized without the dependency on global

TABLE 3. Summary of mode shape techniques.

Ref.	Metric	Method	Criterion	Test
[64]	Mode angle	Fourier transform	Most leading angle	2019 EI at 0.25 Hz
[65]	Phase, magnitude and frequency	Linear system model	Largest value in vector	16 machine ISO NE at 1.5 Hz
[66], [67]	Angle, mode	Oscillation centre	Multiple oscillation sources	Three-machine system
[68]	Relative phase shift	VMD	N/A	Two-area system, POSOCO
[69]	Dissipating potential, oscillation magnitude and mode angle	Weighting of three	No topology	179-bus WECC model and EI event
[70], [71]	Voltage angle difference	Space-time characteristics	Low-frequency and out-of-step	Yunnan Power Grid
[72]	Phase	Relative damping contribution	Least damping contribution	ISO NE at 0.9 Hz with 39 PMUs
[73]	Amplitude	Ratio of harmonic to fundamental	Highest ratio	ISO NE 2017 at 1.13 Hz, EI 2019 at 0.25 Hz, WI 2016 at 1.14 Hz
[74]	Angle difference	Resonance with natural oscillation	Largest angle difference between forced and natural	EI in Florida 2019 at 0.25 Hz and in Georgia 2016 at 0.7 Hz
[75]	Magnitude, phase	Transfer function	Highest magnitude or leading phase	2-area and 16-machine
[76]	Damping ratio, modal frequency, the mode shape	Frequency decomposition, Pearson correlation	Highest correlation	Simulation with 1.35 Hz
[77]	Frequency, current magnitude, and damping	Time-stamped waveform	N/A	DFIG

measurements. In [82], to improve the speed of [81], a new method based on dissipation power was proposed by determining the polarity of dissipation power of generators and lines for the energy flow, similar to [41]. It was tested in an actual event in China with a frequency of 0.739 Hz. Reference [83] developed an online monitoring method based on [80].

2) RECENT WORKS

In recent years, the energy technique has attracted great interest due to the wide deployment of PMUs. The method in [41] requires steady-state values of the variables during the transient process, which is not available in a practical network. In [84] and [85], extra processing of the raw PMU data was introduced, including a selection of transient period, fast Fourier transform for a mode of interest, and signal filtering, to create a linear approximation of the dissipating energy flow (DEF), and it then used the change of dissipating energy to localize the source. The method was proven effective by testing multiple simulated cases of sustained oscillations, including both poorly damped natural and forced oscillations and more than 30 actual events in ISO New England (ISO-NE) and two events in Western Electricity Coordination Council (WECC) systems. These test cases were given in [86] and the successful experience of ISO-NE was shared in [7]. Efforts have also been made to speed up the calculation of energy flow by shortening the window of calculation [87]. The assumptions of lossless network and constant power for DEF were explained using passivity theory in [88] and [89].

In [90], the energy at each branch was decomposed into periodic and aperiodic components and the direction along which the aperiodic components propagated and dissipated was used to localize the source. The method was tested in a Chinese network with five interconnected regional grids at 0.7 Hz.

In [91], for low-frequency oscillation with time-varying steady-state points, a new method was proposed to decompose the branch energy into state energy, reciprocating energy, and dissipation energy. Then, the flow direction of the dissipation energy was used to localize the source in the North China Power Grid.

In [92], the energy injected into the generator was decomposed into energy injected by the prime mover system and excitation system. For the energy injected into the grid, the phasor relation between the variations of branch variables was analyzed to identify the energy flow direction. Then, the bus level source localization was achieved using the energy flow direction from phasor analysis, and the control device level localization was achieved using the injected energy of the prime mover system and excitation system of the generator. This method can locate multi-mode oscillations with multiple sources.

In [93], the power system was divided into several large cut sets and these large cut sets were further divided into smaller cut sets based on the WAMS information. WAMS measurements were decomposed into a number of oscillation modes using the Prony algorithm or Hilbert-Huang transform (HHT). For the main oscillation mode, the energy flow was calculated for each large cut set to determine which large cut set has the source. Then this was repeated for smaller cut sets until the localization of the source at the bus or unit. In [94] and [95], the energy method was applied to the case of multiple oscillation sources using both PMU and supervisory control and data acquisition (SCADA).

After these works, there have been continued efforts to improve the energy method in the past few years due to its success. For example, in [96], the energy function was constructed in the complex plane and then the real and imaginary parts of this complex function were weighted according to the R/X ratio and used for localization, in contrast to the original energy method that only uses the

TABLE 4. Summary of early works on energy techniques.

Ref.	Metric	Feature	Test	Freq. (Hz)
[78]	Phase of dominant energy mode	Two groups	19-generator 49-bus model	1.03, 0.37
[79]	Energy flow and peak instantaneous power	Two sides of one device	Distribution feeder in Texas	None
[41]	Energy flow at each bus	Wide area measurement system	2-area 4-machine system and real events in China	None
[80]	Energy with linear equations of motion of rotor	Oscillation by cyclical load	New England 10-machine 39-bus system	0.9898
[81]	Energy injected to network	Energy supply on port	4-machine 2-area system and IEEE-118 bus system	0.77, 0.82
[82]	Dissipated energy variation from disturbance	Remove periodic variation	Two-area with four-machine and Hunan events	0.936, 0.739
[83]	Potential energy	Online real-time	Henan power grid	0.2894

imaginary part. This method was further studied in [97] to propose a dissipating energy pattern recognition process in the frequency domain with limited PMUs and in the phasor domain for inverter-based resources, evaluated in the 240-bus WECC system and actual oscillatory events in ISO New England power system. In [98], a new expression for DEF was obtained and validated over a real event in ISO-NE at 1.13 Hz. In [99], the dominant propagation path of SSO was identified using the oscillation energy of branches under the dominant oscillation mode and the oscillation energy distribution coefficient of each branch to locate the high-risk oscillation area of the system. In [100], model knowledge was used to enhance the DEF method.

In [101], the energy flow in the DEF method was used to group branches using the closed contours method to indicate if the forced oscillation was from a single generator, from a power plant, from a region, or from an operating entity. In [102], the Lyapunov modal analysis was used to estimate the location and structure of inter-area oscillations as well as their interactions on the graph of a power network. The modal indicators used the energy of voltage disturbances accumulated over time rather than the instantaneous dynamics of an individual perturbation. In [103], the data fusion Dempster–Shafer (D-S) evidence theory was used to establish the mass function and the trust degree of each bus, where the mass function was calculated using oscillation energy flow, voltage-based oscillation phase difference, and forced oscillation phase difference. The decision of oscillation source localization was made with the highest synthesis decision value. In [104], multisynchrosqueezing transform was applied to the signal for a time–frequency analysis from which the ridge tracking method was utilized to identify and reconstruct the SSO components, and the DEF method was applied to locate the source and sink of the SSO in the subsynchronous components. In [105], data at local control centers were used to calculate local energy flows embedded in low FO. Then, an average-consensus algorithm was used to exchange local energy flow to detect the cut-set energy and locate the FO source in a distributed manner, with an adaptive minimum cut-set division method based on graph theory.

In [106], the DEF method was applied to power systems with significant integration of wind turbine generation (WTG). The multichannel Prony analysis with Periodogram was used to detect FO and DEF was used to localize them. In [107], [108], and [109], the DEF method was applied to VSC-HVDC, and FACTS with a thyristor-controlled series capacitor (TCSC) and a static synchronous compensator (STATCOM). In [110], the DEF method was applied to HVDC. In [111], the DEF method was used for doubly-fed induction generators (DFIGs).

In [112] and [113], the DEF and mode shape methods were compared. In [114], the SSO power and DEF methods were compared. In [115], three different versions of DEF, the original, FFT-based, deviation-based, were compared.

In summary, the energy method is simple, as the dissipating energy in the network is easier to calculate than other metrics. However, the original energy method is based on some strong assumptions, and in order for the energy method to achieve high accuracy in practical networks, improvements are required to address it. These include energy decomposition, complex energy, lossy networks, and classical loads. As a baseline method, it can also be combined with other methods, such as graph theory, DS theory, and average-consensus, for use in different applications.

IV. OSCILLATION SOURCE LOCALIZATION BASED ON METHODS

The methods used in oscillation source localization include data-driven methods, reference-based methods, learning methods, and transform-based methods. They will be discussed in the following.

A. DATA-DRIVEN

Data-driven methods are measurements-based methods using PMU or SCADA to localize the source of power oscillation without much knowledge of the system model. Their data processing is mainly based on the measurement matrix. Different criteria have been used to identify the source in the data-driven methods.

In [116] and [117], a purely data-driven yet physically interpretable approach was proposed to pinpoint the source of forced oscillation, in the case when there was resonance between forced oscillation and natural oscillation such that traditional methods may fail. All the PMU data were put together in a measurement matrix. Then, leveraging the sparsity of the forced oscillation sources and the low-rank nature

TABLE 5. Summary of recent works on energy techniques.

Ref.	Feature	Test	Freq. (Hz)
[84], [85]	Rate of change of dissipating energy, filtering, transient time	WECC 179-bus 29-generator, ISO NE events	0.2-1.4
[87]	Clustering and modal estimation to shorten data	ISO NE events	0.28, 1
[88], [89]	Justification of DEF with lossy network and classical load	IEEE 39-bus New England, WECC 179-Bus	2, 0.86
[90]	Periodic and aperiodic energies	Chinese network with five interconnected regional grids	0.7
[91]	State, reciprocating and dissipation energies	North China Power Grid	None
[92]	Phasor relation between variations, multi-mode oscillations with multiple sources	4-machine 2-area, East China power grid, WECC 179-bus	0.64, 0.8, 0.65, 0.43
[93]	Cut sets	Yunnan Power Grid	None
[94], [95]	Multiple sources	Kundur, New England	0.2, 0.3
[96]	Complex DEF, weighted with R/X ratio	Kundur 2-area, 240-bus WECC	0.2, 0.379
[97]	Energy pattern recognition	240-bus WECC, events in ISO NE	0.379, 0.614, 7, 19
[98]	New expression of DEF	WECC, ISO-NE event	0.22, 0.37, 1.13
[99]	Dominant propagation path of SSO	4-machine 2-area, 10-machine 39-bus	13 - 41
[100]	Use extra model knowledge	240-bus 178-line WECC	0.379 - 1.19
[101]	Closed contour grouping	EI North America and local events	0.25, 3.3
[102]	Lyapunov modal analysis	IEEE 68 bus	None
[103]	Data fusion D-S evidence theory	WECC 179 bus	0.37-1.63
[104]	Multi-synchro squeezing transform	Three-wind farms, modified IEEE 10-generator 39-bus, NE	20, 13.4
[105]	Distributed with average-consensus	IEEE 39-bus and 162-bus	0.57, 1.03

of high-dimensional synchrophasor data, the measurement matrix was decomposed into sparse and low-rank component matrices using robust principal component analysis (RPCA) for real-time localization. This method did not require any information on dynamical system model parameters or topology and can locate the source of forced oscillations with high accuracy, even with resonance. It was tested in the IEEE 68-bus and WECC 179-bus systems for real-time operation.

In [118], active power measurements from PMUs and impedance matrix and load flow results from SCADA were used to calculate the power change vector, disturbance distribution matrix, and disturbance estimation matrix. Then, the mismatch vector was calculated using the disturbance estimation matrix to estimate the time, size, and location of the oscillation based on the level of agreement between generators. The oscillation source was identified as the one that had less agreement than others. It was tested in the IEEE 39-bus system.

In [119], to improve the method in [116], sparse identification of nonlinear dynamics (SINDy) was proposed as an online purely data-driven method to locate the forced oscillation. In particular, measurements containing rotor angles and speeds were used to form a measurement matrix. Using the measurement matrix and a library, a local minimizer with a non-convex objective function and zero norm penalty term was formulated and solved for a coefficient matrix. An index was calculated from this matrix and the source of oscillation was identified from the peak values of the index. It was tested using the IEEE Task Force test cases library, the IEEE 68-bus system, and the WECC 240-bus system for frequencies of less than 1 Hz.

In [120], due to the limited availability of PMUs, SCADA data from the Eastern Region of the Indian power system were combined with PMU data in pattern mining algorithm (PMA) and maximal variance ratio algorithm (MVRA) for detection of the source of forced oscillation events. It was tested using the 2017 forced oscillation event at 0.083 Hz and the 2018 event at 0.2 Hz in India. The same method was used in [121].

In [122], a system agnostic localization of oscillations (SALO) algorithm was proposed, where the PMU measurements were used to form a measurement matrix. Source localization was achieved by performing a simultaneous dynamic model identification using maximum likelihood without knowledge of system topology and parameters. This method requires full PMU coverage on all buses. In [123], the method was extended to realistic scenarios with partial PMU coverage and including buses without inertia or damping, such as passive loads and inverter-based generators. Kron reduction was applied to the maximum likelihood estimator to reduce parameters.

In [124], to remove the requirement on model parameters in previous work, a new method using the swing equation was proposed by calculating a frequency domain parameter using measurements. It was tested in a western North American system at 0.37 Hz.

The propagation of forced oscillation among different generators exhibits causalities between source generators and effect generators, where the source is the cause while other generators are the effect. In [125], the spectral Granger causality analysis was used to locate the oscillation source. The parameters were estimated using data with the AR model and feature selection. A method of arrival delay estimation of forced oscillation was also proposed to determine the arrival sequence of forced oscillation at different generators. They were tested in the 3-machine 9-bus system and 25-machine 162-bus system at 1.316 Hz. A similar causality analysis was used in [126] and tested in the IEEE 68-bus system at 1.705 Hz.

In [127], a model-enhanced method was proposed to utilize the advantages of both model knowledge and measurements. First, the system transfer function was obtained by assuming the linearized dynamical model. Then the transfer function and the PMU measurements as outputs were used to calculate the forced oscillation as inputs by least-squares. The inputs were used to localize the source.

In [128], for a continuous-time linear dynamical system, each input was modeled as an output of a zero-input latent linear dynamical system with one output and an arbitrary number of latent states. Then, a deterministic subspace model identification method was used to jointly estimate the matrices of the (sampled) linear system and also the sources of the locations (that is, the inputs with non-zero entries) by solving a simple least squares problem using PMU data collected.

In [129], [130], and [131], the measurement-based graph theoretic method was used to localize the source. First, the aggregate electro-mechanical model of the power system was shown to be a generic nth-order asymmetric networked dynamic system. Then, an input localization method based on the properties of the weak nodal domains corresponding to the first p dominant eigenvalues was proposed.

In summary, most data-driven methods are inspired by the fact that power system topology and parameters are difficult to obtain or unreliable due to their complexity. Hence, these methods often treat the power system as a black box with the measurements as outputs and the forced oscillations as inputs, and they rely heavily on the effectiveness of signal processing techniques. Nevertheless, there is still a degree of model information required, such as the linearized model, the latent model, and the graph theory. Such methods also require extensive use of PMU data but this is often limited, in which case SCADA data can be used complementarily. Note that the data-driven methods are not exclusive to the techniques based on metrics discussed in the previous section, such as the energy technique and the traveling wave technique. For example, the data-driven method in [125] also used the traveling wave. Other data-driven methods include [132] that used a Luenberger observer and [133] that used correlation. They are summarized in Table 6.

B. REFERENCE-BASED

The reference-based methods can be considered as a special category of data-driven methods. They also use data but test the difference between measured values and predicted values during normal operations and forced oscillation. This difference is used for oscillation source localization.

In [134] and [135], a data-based residual analysis method was proposed that only used measurements local to each power plant. System identification was used to identify the transfer function representing the behavior of the plants during normal operations. When forced oscillations occur, the measured response at each power plant was compared with the predicted response using the model identified in normal operations. The power plant with the largest residual between the predicted and measured responses was considered as the source of the forced oscillations. A similar method was discussed in [136] and [137].

In [138], the difference between the active power generated from hybrid dynamic simulation (solving the differential algebraic equations with some known measurements) and the measured active power was calculated and the source of oscillation was identified as the one with the largest difference.

The idea in [139] was very similar to [134] and [135], except the impulse response was used instead of the transfer function. Particularly, during normal grid operations, data were collected to recover the impulse responses in the small signal regime, without the system model. When forced oscillation occurred, the measured values and the predicted values using the impulse response were used to fit the least-squares (LS) error to find the source.

In [140] and [141], the difference between measured outputs and predicted outputs was formulated as a variant of the group linear absolute shrinkage and selection operator (LASSO) estimator to find the location of the source of oscillation.

In [142], instead of transfer function or impulse response, the difference between the measured and predicted admittance matrix for each generator was calculated and the source was identified as the generator that gave a large difference.

In summary, the reference-based methods are purely data-driven by formulating an error optimization problem using either transfer function, impulse response, active power, or admittance matrix and then solving the problem using different methods to localize the source of oscillation. They do not require any system parameter information or topology. However, they do have high computational complexity when the system has a large number of generators or a long record of data, as the measurement matrix will be very large.

C. TRANSFORM-BASED

The transform method refers to the use of transform domains, such as Fourier and wavelets, in data processing, as it is sometimes easier to find the modes in the transform domain than in the time domain. In fact, this method has already been used in some of the works discussed in the previous section, such as VMD in [68], FDD in [76] and multisynchrosqueezing transform in [104]. The energy method also requires the use of a fast Fourier transform (FFT) to extract the mode of interest before calculating the energy flow. Specifically, this subsection focuses on data pre-processing using the Fourier transform, wavelet transform, and mode decomposition.

1) FOURIER

The Fourier transform is the earliest transform developed for signal processing. It converts a time-domain signal into

TABLE 6. Summary of data-driven methods.

Ref.	Method	Feature
[116], [117]	Decompose measurement matrix into sparse and low-rank components using RPCA	Resonance between forced oscillation and natural oscillation
[118]	Active power from PMUs and impedance and load flow from SCADA to form the mismatch vector	Time, size, and location of the oscillation
[119]	Sparse identification of nonlinear dynamics (SINDy)	The source of oscillation was identified from the peak values of the index
[120], [121]	PMA and MVRA	Use both PMU and SCADA
[122]	Simultaneous dynamic model identification using maximum likelihood	No knowledge of system topology and parameters but full PMU coverage
[123]	Kron reduction, maximum likelihood	Partial PMU coverage and including buses without inertia or damping
[124]	Swing equation	Frequency domain
[125]	Spectral Granger causality analysis, arrival delay estimation	Causality and delay at generators
[126]	Causality analysis, sparse principal component analysis	Starting point of forced oscillations
[127]	Model transfer function and PMU measurements for outputs, least-squares	Both model information and measurements
[128]	Subspace model identification	Oscillation as output of a zero-input latent linear dynamical system
[129] - [131]	Graph theories	Input localization for a nth-order asymmetric networked dynamic system
[132]	Luenberger observer	Localization of oscillation source and estimation of its amplitude
[133]	Correlation	Correlation between each bus disturbed and the response from the system

a frequency-domain signal. This transform has a physical meaning and is also simple and thus, it is widely used.

In [143], FFT was applied to the measurements. Then, a data-driven method using a Bayesian framework with a two-stage maximum *a posteriori* optimization algorithm was employed to locate the source of oscillation. Unlike the data-driven methods in the previous subsection, this work performed FFT first. In [144], FFT was applied to the measurements of the active power to extract the dominant component of the oscillation and then the energy method was used to localize the disturbance source. In [145], the short-time Fourier transform (STFT), STFT-based synchrosqueezing transform (FSST), and the second order FSST (FSST2) were used for non-stationary FO to obtain its multi-channel time-frequency (TF) representation (TFR) and the DEF method was then used to localize the source. In [146], FFT with a moving window was performed on the frequency data and then the traveling wave method was used to localize the source. In [147], discrete sine transform was applied to the frequency variations at each bus, and the bus with the largest amplitude of frequency variation was considered as the source.

In [148], cross-power spectral density (CPSD) of synchronized voltage magnitude and voltage angle versus active power and reactive power signals were calculated using FFT. The largest positive imaginary part of a CPSD was used as an indicator of the oscillation source. The type of an oscillation source was determined by comparing the spectral densities of active and reactive power. VMD was used to extract the dynamic component of the signals with oscillation. In [149], the kurtosis and the power spectral density of the real-time measurements at each bus were calculated to distinguish between weakly damped oscillation, limit cycle, and forced oscillation, and then the absolute value of kurtosis or spikes in PSD was used to locate the source. In [150], the derivative constrained minimum variance distortionless response (MVDR) algorithm was used to calculate the coherence spectrum for multi-delay signals. A higher coherence spectrum close to 1 indicates that the bus is closer to the source of oscillation.

2) WAVELETS

Wavelet transforms are developed after the Fourier transform to process data in both time and frequency domains. Over the decades, they have been proved effective in dealing with transient phenomena that are often observed in nonlinear and non-stationary data.

In [151], Morlet wavelet filtering was first employed to extract electrical quantity data in a single mode. Then, a subspace dynamic mode decomposition algorithm was applied to estimate the parameters of the mode. After that, the dissipation area difference ratio based on the energy flow theory was used to localize the source of oscillation.

In [152] and [153], the synchrosqueezing wavelet transform (SWT) was applied to the PMU measurements. Then, the SWT-based dissipating energy flow (DEF) model in the time-frequency domain and dissipating energy spectrum (DES) model in the frequency domain were obtained by extending the traditional DEF model. In [154], the wide-area measurement data were processed by using the synchrosqueezing wavelet to extract the oscillation mode parameters. Then, the dissipated energy flow of each generator was calculated using the extracted mode parameters to localize the forced oscillation source. Similarly, in [155], the multisynchrosqueezing transform (MSST) was applied to wide-area measurement data, and ridge extraction was used to obtain the frequency trajectory in the time-frequency plane. Then, a time-frequency domain dissipation energy flow calculation method was used. In [156], Fourier synchrosqueezing transform (FSST) was used to provide a concentrated time-frequency representation of the data and DEF was applied to the extracted components to locate the source of forced oscillations.

A review of the use of wavelets in power system dynamics analysis was provided in [157].

3) MODE DECOMPOSITION

Mode decomposition is a further development of wavelet transform. It uses different empirical principles to decompose the time series into a sum of components called modes. For example, the empirical mode decomposition (EMD) decomposes a time series into intrinsic mode functions combined with the Hilbert–Huang transform (HHT). The variational mode decomposition (VMD) uses the variational principle to decompose a time series into modal signals.

In [158], using the active power and frequency of the transient phase of an oscillation, the dominant mode of electrical components was extracted by VMD. Then, the oscillation energy was calculated using these values, and the rising or falling trend of the oscillation energy was used for localization.

For a transmission line connecting the disturbance source, the oscillation phase of the voltage angle (frequency) of the bus at the end near the disturbance source will advance away from the oscillation phase of the voltage angle (frequency) of the bus at the disturbance source. In [159], EMD was used to extract the dominant oscillation mode, and the Hilbert transform was then used to calculate the oscillation phase difference to localize the source.

In [160], the raw PMU data was decomposed into a series of intrinsic mode functions (IMFs) using EMD. The most appropriate IMF containing the vital information was selected using the correlation technique. Then, the segmented power spectrum density (PSD), excess kurtosis, cross PSD, etc. were used to localize the source.

In [161], a multivariate variational mode decomposition (MVMD) was used to decompose the measurements in the time-frequency (TF) plane at each generator. The IMFs associated with the forced oscillation mode were extracted using the relative energy weights. Then, the DEF method was used to localize the source of oscillation.

In [162], dynamic mode decomposition (DMD) was applied to the PMU measurements to exploit the spatio-temporal patterns of dominant dynamics. A two-tier structure was further used to improve the robustness and accuracy.

In [163], the methods in [153] and [160] were combined to use EMD to decompose the measurements and IMFs associated with the forced oscillation mode were extracted using the relative energy weights. Then, the DEF method was used to localize the source of oscillation.

In summary, the transform methods refer to those methods that apply sophisticated signal processing algorithms to decompose the measurements before any further processing. They are useful in removing noise and interference in the data. This de-noising allows more accurate localization. Most of the transform methods are combined with the energy method, as can be seen in Table 7. However, other metrics can also be used.

D. LEARNING-BASED

Artificial intelligence has seen a great development in recent years, and it has a great impact on many aspects of our lives, including power systems. Many learning-based methods have been applied to power system control and operation, including the localization of oscillation sources.

Starting from machine learning methods, in [164], an online dynamic event location method was proposed based on an offline hierarchical clustering of generators into coherent groups. This unsupervised learning method divided the generators into groups and selected one in the offline phase to represent each group in the later online phase. It then used its rotor frequencies to identify the group with the largest initial swing as the event location. In [165], the supervised random forest method was proposed by first establishing the dynamic model of the system, deriving the state-space equations, and then selecting key dynamic characteristics to train the learning model to find the mapping relationships between the feature data and the oscillation area. In [166], the oscillation energy method, the oscillation phase difference method, and the forced oscillation phase difference location method were fused by using the evidence theory, and the fusion probability was trained by using the supervised support vector machine (SVM) method. In [167], using time series motifs, the motif embedding correlation field (MECF) method was proposed to characterize higher order temporal structures of power system time series and employed in the unsupervised learning t-distributed stochastic neighbor embedding to localize the source of the FO, including a single FO, FO with resonance, and multiple concurrent FOs. In [168] and [169], the improved k-nearest neighbors learning was used with the Mahalanobis distance of multi-variate time series from active powers and rotor angles to find the source of oscillation. In [170], decision tree, SVM, and random forest were used in a framework called credibility search ensemble learning for source localization.

The machine learning methods are relatively simple and are often explainable. These advantages are preferable in power oscillation localization, as power system operators need to not only find the source of oscillation but also show the regulators or the customers how they are found. However, machine learning has limited learning capability. Thus, most learning-based methods choose to use deep learning (DL).

A widely used deep learning method is transfer learning. In [171], both system-level and area-level localization were considered. The two-stage deep transfer learning was applied. The first stage repurposed the learned features from a pre-trained deep convolutional neural network (CNN) to improve the learning of system-level localization. The second stage transferred the knowledge acquired from the first stage to aid area-level localization learning. In [172], firstly, the active power measurements at all generators were applied to short-time Fourier transform to obtain their two-dimensional time-frequency spectrograms. Then, using color linear mapping, they were converted into images and image

TABLE 7. Summary of transform-based methods.

Ref.	Transform	Method
[143]	FFT	Data-driven Bayesian
[144]	FFT	DEF
[145]	STFT, FSST, FSST2	DEF
[146]	FFT	Traveling wave
[147]	FFT	Amplitude of CPSD
[148]	DST	Amplitude of frequency variation
[149]	FFT	Kurtosis and PSD
[150]	MVDR	Self coherence spectrum
[151]	Morlet wavelet	Dissipation area difference ratio
[152], [153]	Synchro squeezing wavelet	SWT-based DEF and DES
[154]	Synchro squeezing wavelet	DEF
[155]	Multi-synchrosqueezing transform	DEF
[156]	Fourier synchrosqueezing transform	DEF
[158]	VMD	DEF
[159]	EMD	Phase difference
[160]	EMD	Excess kurtosis, cross PSD
[161]	MVMD	DEF
[162]	DMD	Two-tier time analysis
[163]	EMD	DEF

classification was applied. After that, transfer learning was employed to transfer image recognition knowledge to source localization. In [173], oscillations caused by the interaction between the multiple voltage source converters in the wind farm grid-connected system were considered. To solve the problem of the lack of oscillation data and the inability to label in the real system, simulation was first performed to generate large batches of labeled training samples using active powers. Then, the common features of the samples between the simulated system and the real system were learned through the transfer component analysis algorithm. Finally, a classifier was trained to localize the source. In [174], for SSO in systems with grid-connected permanent magnet synchronous generator (PMSG), simulation was first performed to obtain the training data, extract features, and establish models using CNN. Then, deep transfer learning was applied by adding regular parameters to the training model and fine-tuning the final trained model to localize the oscillation source in the actual system. Similarly, in [175], [176], and [177], again, due to the lack of sufficient labeled data for DL training in an actual power system, a deep transfer learning (DTL) architecture was proposed to transfer knowledge from a simplified simulated power system to an actual power system.

In addition to transfer learning. other DL methods are also used. For example, in [178], the graph data was constructed using the node voltage phase angle measurements and grid topology information. Then graph CNN was used to extract the oscillation space features, and the gated recurrent neural network (RNN) was used to extract the temporal correlation of oscillation data at multiple nodes. The spatial and temporal characteristics were fused by the spatio-temporal graph convolution unit to train a temporal graph CNN for classification. In [179], a new method was proposed using long short-term memory (LSTM) variational auto-encoder signal compression and graph CNN to compress the measurements at the substation and then localize the source through graph CNN at the main station.

In [180], compressed sensing-based sparse signal sampling and auto-encoder were used to compress raw PMU measurements at substations and then apply the compressed signals at multiple substations to CNN-LSTM as inputs to identify the source as the output. In [181], the time-varying features, such as frequency drift caused by the random volatility of wind farms, were considered. It proposed an SSO localization method using an enhanced short-time Fourier transform to obtain time-frequency distribution (TFD) images and a CNN to extract SSO features and localize the source. In [182], the variation of oscillation energy in time and the direction of energy flow in space were used to construct the feature images. Then, the quaternion feature set CNN (QFS-CNN) method was proposed to locate the SSO sources. In [183], a digital twin-based oscillation source localization method was proposed. First, the generative adversarial imputation network was used to repair the missing samples. Then, the spectrum of the oscillation signal was extracted using the fast Fourier transform. Finally, branch potential energy was used as the input to LSTM and CNN for localization. In [184], the phase angle and rate of change of frequency trajectories were used to determine two sets of wave arrival times at each generator. Then, a CNN was utilized to determine the wave arrival order to select the more suitable set of wave arrival times. Next, the oscillation intensity at each FDR was triangulated using phase angle trajectories in the center of inertia (COI) coordinate system for localization.

In [185], a hierarchical deep-learning neural network was proposed to effectively handle the FOs in a micro-grid with distributed converter-based resources. It was divided into three levels for FO detection, identification, and mitigation. In [186], a novel DL-based method was proposed to find the oscillation source by using the spectral information extracted from the sliding-window time-series data from simulated PMU measurements over a range of randomly chosen oscillatory events. In [187], the active power, reactive power, FO frequency, and DEF were used as input to a transformer-based DL framework to localize the source. In [188], an artificial neural network classification model was used to determine the relative position of SSO using local measurements at substations in terms of DEF and SSO power and then decisions from all substations were combined at the main station for localization. In [189], sparse learning was used to determine the equivalent damping coefficients and topological parameters of the network and the most dominant nonlinear term from a set of dictionary functions was selected as the source.

In summary, the learning-based methods use either machine learning or deep learning. The machine learning methods are simple but have relatively limited capability in complicated power systems. The deep learning methods can improve accuracy but require more training data, while practical networks may not have sufficient labeled data. Hence, transfer learning can be used to learn simulated data first and then transfer the knowledge to a practical system. In addition, LSTM and CNN are frequently used to extract temporal and spatial features for learning. Some of the learning methods also use various ways of data compression, such as autoencoder and sparse sampling. They also use different methods to obtain the two-dimensional data, such as Fourier transform. They are summarized in Table 8.

V. INDUSTRY PRACTICE

Power oscillation is a common problem in most grids. Therefore, it has attracted attention from power system operators around the world. Below are examples of how some of them deal with power oscillations available in the public literature.

In [190], [191], and [192], a wide-area monitoring tool called Eastern Interconnection Situational Awareness Monitoring System (ESAMS) and developed and tested in the Eastern Interconnection of the US was discussed in detail. This tool uses the DEF method to localize the source of oscillation using PMU measurements.

In [193], the Western Electricity Coordinating Council (WECC) developed a forced oscillation detection & source location tool in the Reliability Coordinator (RC) function of the Western Interconnection. It has four main components: (1) Montana Tech's Modal Analysis Software (MAS) engine; (2) Washington State University's Oscillation Monitoring System (OMS) software; (3) Forced Oscillation Detection and Source Location Algorithms (FODSL); and (4) their in-house visualization tool and alarming logic. The source location uses the PMA and MVAR methods in [120] and [121].

In [194], the DEF method was implemented in the Northeastern Thailand Power Grid. In [195], the mode shape method was tested in the Ecuadorian National Interconnect System, an interconnected system between Ecuador and Colombia, using their WAMS.

In [196], [197], and [198], using the wide-area frequency monitoring system (FNET) developed by Virginia Tech for the Eastern United States Interconnected System (EUS), the traveling wave method was tested to localize the source of oscillation.

In [199], the DEF method was used in Ireland's All-Island transmission system to localize very low-frequency oscillations (VLFOs) between 0.03 and 0.08 Hz. In [200], Fingrid used a data-driven method in their real-time monitoring system to investigate the inter-area oscillation for the Nordic synchronous system interconnecting Finland and Sweden, when the forced oscillation and inter-area natural oscillation were in resonance.

It is noted that the earlier developed tools tend to use traveling wave and mode shape methods, while the more recent ones tend to use the DEF method.

VI. OPEN CHALLENGES

Despite the great effort from both academia and industry to address the localization issue of power system oscillation sources, a few open challenges still remain. They are outlined as below.

A. LIMITED PMU

Many of the existing methods rely heavily on the availability of PMUs or other measurement systems to acquire data on the status of the network. For example, the energy method needs PMUs at each generator in order to calculate the energy flow for localization. The data-driven and error-based methods also require measurements at all generators in order to identify which one or ones of them are the oscillation source. However, this is not always possible, especially for older power systems or older parts of the power systems. Hence, one challenge is to identify the source of oscillation as accurately using as few PMUs as possible. This could be addressed by combining PMU with SCADA or by developing source oscillation at the system level, then the area level, and finally the generator level in a hierarchical manner.

B. LIMITED DATA

Power system oscillations are becoming more and more frequent in recent years, due to the high penetration of renewable sources and other factors. However, forced oscillations are still relatively rare events in the power system. On the other hand, in order for the learning method to work effectively, a lot of labeled data with actual events is required to train their models. In the existing methods, transfer learning has been used to train the models in simulated systems with as many cases as possible and then transfer them to the actual systems. However, the simulated systems cannot fully duplicate the actual systems. This reduces the accuracy of the localization methods. Thus, a new challenge is to generate as many labeled data as possible that resemble in the actual systems for the learning methods. This could be addressed by adopting the newest advances in artificial intelligence that deal with small sample sizes or missing data or by increasing

TABLE 8. Summary of learning-based methods.

Ref.	Learning	Feature
[164]	Clustering	Rotor frequencies
[165]	Random forest	State-space equations
[166]	SVM	Energy, phase difference
[167]	t-distributed stochastic neighbor embedding	Motif
[168], [169]	k-nearest neighbors	Mahalanobis distance
[170]	Decision tree, SVM and random forest	Credibility search ensemble learning
[171]	Deep transfer learning	Transfer system-level localization to area-level
[172]	Transfer learning	Transfer image recognition to source localization in power
[173] - [177]	Deep transfer learning	Transfer features from simulation to practice
[178]	Graph CNN and RNN	Spatial-temporal characteristics, grid topology
[179]	LSTM, graph CNN	Substation data compression and main station localization
[180]	Sparse sampling and auto-encoder, CNN-LSTM	Substation data compression and main station localization
[181]	CNN	Short-time Fourier transform to obtain time-frequency distribution images
[182]	QFS-CNN	Energy variation in time and energy flow in space
[183]	Generative adversarial imputation, LSTM, CNN	Digital twin, branch potential energy
[184]	CNN	Phase angle, rate of change of frequency
[185]	Hierarchical deep-learning neural network	FO detection, identification, and mitigation
[186]	LSTM	DEF
[187]	Transformer	Active, reactive power, FO frequency, and DEF
[188]	Artificial neural network	Local DEF and SSO power at substations and decision at main station
[189]	Sparse learning	Equivalent damping coefficient

the complexity of the simulated systems to duplicate the actual systems as much as possible.

C. NONLINEARITY

The power system is naturally a nonlinear system but in most existing methods, it is approximated by a linear system. This is more of the case in the data-driven and reference-based methods, where the transfer function and the impulse response are only meaningful for a linear system, even though these methods do not require much system model information. This approximation error will lead to the localization error for the oscillation source. Thus, one challenge is to reduce the localization error caused by this approximation error. One solution is to use more accurate models of the power system in these methods. Another possible solution is to test the linearity of the concerned system before applying any source localization method during the data pre-processing step. For example, some methods, such as mode decomposition, can deal with nonlinear systems. Also, machine learning could be used to classify the system first.

D. OTHERS

Other challenges include the following. The DEF method has been proved successful by many simulations and case studies. However, in order to make it efficient, it is always necessary to fine-tune its steps and parameters in practice. For example, the transient time needs to be chosen carefully. The mode of interest needs extra care when there are multiple sources or when there is resonance between forced oscillation and natural oscillation. It would be desirable to find a universal or pervasive DEF method that can be adapted to all cases without much fine-tuning. Also, it could be useful to combine all metrics in source localization. There have been some works that fuse decisions from traveling wave, mode shape, and energy methods, such as evidence theory. However, accuracy improvement may be possible by performing data fusion, for example, by using traveling wave and mode shape parameters in the calculation of the energy flow at each bus. Also, statistical signal processing has been developing in recent years. More advanced decomposition or transform methods could be used to decompose the measurements to remove as much noise as possible. In addition, challenges in communication issues, cyber-attacks, measurement delays, and on-grid and off-grid issues should also be considered in environments requiring real-time responses. Addressing these issues is essential for maintaining system stability and reliability.

VII. CONCLUSION

In this survey, the localization techniques for the source of forced oscillation have been reviewed. Some important concepts on oscillation and important metrics for oscillation source localization of the power systems have been presented first. Then, more than 150 techniques for oscillation source localization have been discussed. These techniques either use different metrics of the power system, such as damping torque, mode shape, and energy flow, or use different methods, such as data-driven, machine learning, and Fourier transform, to locate the source of oscillation. Different features of these techniques have been explained. Their main principles, advantages, and disadvantages have been studied, and their industry practices have been discussed. Based on this study, some open challenges for oscillation source localization have been outlined. This survey aims to provide researchers and engineers with a complete reference on most existing methods in the literature to localize the source of oscillation for their needs.

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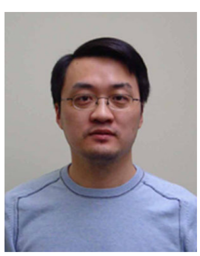

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