J. Mod. Power Syst. Clean Energy (2017) 5(2):151–159
DOI 10.1007/s40565-016-0216-5

Location methods of oscillation sources in power systems: a survey

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Abstract The deployment of a synchrophasor-based wide-area measurement system (WAMS) in a power grid largely improves the observability of power system dynamics and the operator's real-time situational awareness for potential stability issues. The WAMS in many power grids has successfully captured system oscillation events, e.g. poorly damped natural oscillations and forced oscillations, from time to time. To identify the root cause of an observed oscillation event for further mitigation actions, many methods have been proposed to locate the source of oscillation based on different ideas and principles. However, most methods proposed so far for locating the oscillation source in a power grid are not reliable enough for practical applications. This paper presents a comprehensive review of existing location methods, which basically fall into four major categories, plus a few other methods. Their advantages and disadvantages are discussed in detail. Some trends and challenges on the problem of oscillation source location are pointed out along with potential future research directions. Finally, a practical, general scheme for oscillation source location using available location methods is suggested and analyzed.

Crosscheck date: 24 March 2016

Received: 17 November 2015 / Accepted: 20 April 2016 / Published online: 27 July 2016

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Keywords Power oscillation, Oscillation source location, Traveling wave, Damping torque, Mode shape, Transient energy, Oscillation test cases library

1 Introduction

Damped oscillations are a normal phenomenon for any disturbed system showing that the system is approaching back to its equilibrium. However, sustained oscillations could happen in reality where the possible causes include improper operating conditions, periodic disturbances or malfunctioning controllers. Such unexpected sustained oscillations may reduce the power transfer limit and even result in detrimental consequences on the system equipment. To solve this problem, researches on the analysis, detection, classification, location and control design have always been active during the past several decades while only a few of them have been integrated into system control centers to help system operators [1, 2].

Since sustained oscillations represent a risk for instability or insecurity of power systems, they should be mitigated as soon as possible. The location of the oscillation source is usually a prerequisite of the mitigation actions and the elimination of the source would always be the most straightforward and effective remedy. This paper presents a survey focusing on the methods for locating the oscillation source.

In the current literature, two types of mechanisms for sustained oscillations, i.e. poorly damped natural oscillations and forced oscillations, have been extensively investigated and explained for observed oscillation events, while some other mechanisms have also been discovered in analyses [3, 4] which are based either on Hopf bifurcation caused by slowly varying parameters or on practically impermissible nonlinear behavior of the system, e.g. out-of-step condition. The discoveries and investigations of these mechanisms not only provide a better understanding of the oscillation phenomenon in power systems, but also are of fundamental importance for laying foundations for different location methods.

Usually, the oscillation source is implicitly defined as a physical device which causes oscillations following a certain mechanism. In practice, causes of sustained oscillations could be the excitation system [5], diesel engine [6], synchrotron as a cyclic load [7], control valve [8], turbo-pressure pulsation [9], governor control [10], asynchronous parallelizing of synchronous generators [11] and improper parameters for the steam turbine controller [12], et al. The purpose of a location method is to find the geographical location of the source, e.g. down to the substation level or control block level. This paper will cover the location methods down to the substation level, while the time localization [13] or device level localization [14–16] are not the focus of this paper.

Generally speaking, the basic requirements for location methods should include (1)–(3) below. In practice, besides the basic requirements, desired location methods should further include (4)–(9).

(1) A rigorous theoretical foundation
(2) The adaptability to different network topologies, different causes of oscillations and different models of dynamic elements that exist in reality
(3) The ability to reliably locate the source of oscillation without any false alarm
(4) Fully measurement-based, i.e. free of the system model
(5) Free of additional equipment or only requiring the minimum equipment to be installed that are inevitably necessary
(6) Able to provide useful information even with partial observability, i.e. when only partial system states are monitored
(7) Robustness against measurement noises and even missing data
(8) Computationally efficient
(9) Capable of working continuously in real time

However, many location methods in the current literature cannot even meet the above basic requirements. Thus, they are not ready for practical use.

This paper will summarize the principle, advantages and disadvantages of each reviewed method. Then, a discussion is provided on the trends and challenges to the location of oscillation source. Finally, a general scheme is suggested on how to utilize current available methods in practice and the conclusion is presented.

2 Summary of the survey

The oscillation source location problem has raised lots of attentions in the past decade and many papers on this topic have been published since 2010, including 30 journal papers, 8 conference papers and 1 dissertation. These publications can be classified into four major categories plus a few other methods: 6 papers based on traveling wave, 2 papers based on damping torque, 3 papers based on mode shape estimation, 19 papers and 1 dissertation based on energy and 8 papers using other methods. Figure 1 shows how many papers published in each individual year and how many papers had been published by each year since 2010. Although this review only covers most related papers from IEEE Xplore and China National Knowledge Infrastructure (CNKI), it should be able to represent most types of methods for locating the oscillation source to the best of our knowledge.

3 Traveling wave based methods

Traveling wave based methods utilize the principle of the electromechanical wave propagation [17] to locate the oscillation source. Ideally, if the accurate detection of the arrival time of the oscillation at different locations and the actual wave speed map [18] were both available, the source location result should be correct and accurate. It is shown in [19] that the earliest detected peak of the oscillation always first appears at the generator with forced oscillation, i.e. oscillation source. Such phenomenon is claimed in another way [20] that the oscillation phase of the bus far away from the disturbance is lagging that of the bus close to the disturbance.

The similarity function is adopted in [21] for detecting the time differences of the arrival times among different generators connected to a common bus using terminal voltages, while the leading generator is identified as the oscillation source. To deal with large scale power systems, an additional device called voltage measuring unit (VMU) is introduced in [22, 23] to overcome the data quality issue

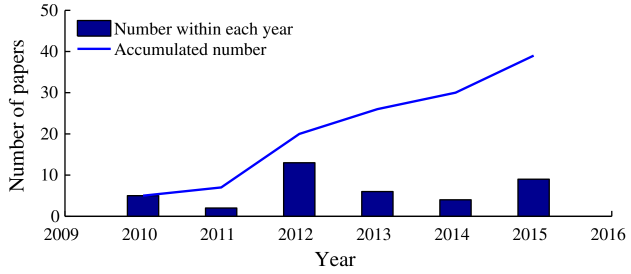

Fig. 1 Publications on oscillation source location

of PMUs. With the assumption that the wave speeds throughout the network are roughly the same, the oscillation source is identified as the location associated with an abnormal wave speed. This method not only requires additional equipment to be installed at some designed locations, but also may possibly misjudge the source location when wave speeds vary significantly throughout the network or when the actual source is close to a certain VMU. A similar method in [24] utilizes the PMU data to locate the source, which employs the least mean square method to estimate the time differences of oscillation arrival times between different locations.

Traveling wave based methods only require measurements corresponding to the a few starting periods of the oscillation to determine the arrival time or time differences between different locations. The advantage of this category of methods is their fast response. Regardless the PMU data quality issue, to make these methods applicable in practice, the detection accuracy of arrival time, the impact from the non-constant wave speed throughout the network and the adaptability to different network topologies should be first investigated and guaranteed.

4 Damping torque based methods

In the damping torque based methods, the generator with a negative damping torque coefficient is identified as the oscillation source. The development of this category of methods depends on the extension of the damping torque concept from a single-machine-infinite-bus system (SMIB) to a multi-machine system.

The concept of damping torque was first introduced to offer a physical insight to system stability problem on an SMIB system [25]. For an SMIB system, the damping torque coefficient can be estimated using the system response by using the least square method [26, 27] or Kalman filter [28]. To extend the concept to multi-machine power systems, the first attempt in [29] estimates the damping torque for each single generator using its own electrical torque, rotor angle and rotor speed trajectories based on the least square error. However, this intuitive extension is found to be valid only when the speed deviations for all other generators are zeros, while it is not tenable in general [30]. Another extension of this concept is mentioned in [31], where the damping torque coefficient for the same generator is supposed to be different with respect to different oscillation modes such that it should be calculated separately for each mode. Thus, the damping torque of a generator in a multi-machine system could be estimated using the system trajectories based on a certain modal analysis method, like total least square-estimation of signal parameters via rotational invariance technique (TLS-ESPRIT) [31] or Prony [32].

The damping torque based location methods have clear physical meaning and could be applied locally for each individual generator, i.e. distributed implementation. Thus, this type of methods could be promising for locating the source which has bad damping. However, this category of methods may fail to work under some forced oscillation cases [33]. In addition, to estimate the damping torque from system trajectories, the measurements of generator electromagnetic torque, rotor angle and speed are often required, which, however, are not always directly measured by present PMUs.

5 Mode shape estimation based methods

Mode shape represents the relative magnitude and phasing of the oscillation throughout the system. It is defined based on the right eigenvectors of the state matrix of the linearized system model. However, the accurate system model is often difficult to obtain and the model based mode shape analysis has only been applied to test systems for a better understanding. To utilize the mode shape information in real systems, many measurement-based methods for estimating the mode shape have been proposed. An overview on existing estimation techniques using either ring-down signals or ambient signals can be found in [34] and its references.

This category of methods locates the oscillation source by estimating the mode shape using measurements from different locations and then identifies the source based on the mode shape. A phenomenon is discovered in [35] on a 2-machine example that the generator leading in mode shape phase contributes less damping. Then, it is intuitively concluded that the leading generator is the oscillation source. For large power systems, the leading generator in an identified leading group is identified as the oscillation source. Although this method is able to identify the oscillation source in many tested cases, it may possibly fail or provide wrong results [33] and the fundamental location principle has not been rigorously proved. Paper [36] compares the mode shape phasing difference between the deviations of mechanical power and electric power for each individual generator, and identifies the generator whose mechanical power is leading the electric power as the oscillation source.

The existing mode shape estimation based location methods always attempt to support their principles by finding a link to the damping concept. There is a lack of investigations on under what conditions the estimated mode shape from measurements conveys the information for locating the oscillation source. However, it was reported that under resonance condition the estimated mode shape from measurements could be quite different compared to the one from model-based eigenanalysis [37] and mode shape information may not help in locating the forced oscillation source [38].

6 Energy based methods

Transient energy function (TEF) is an application of Lyapunov function in power system stability analysis [37], which is usually defined as the sum of the kinetic and potential energies of all generators in the synchronous coordinate framework.

Papers [39] and [40] introduced the TEF based method for analyzing and characterizing the power system oscillations. Papers [41–43] extended the transient energy concept from generators to the branches in the network, which is called branch potential energy (BPE). The first attempt to apply the TEF or BPE to locate the source of forced oscillation is presented in [44] by monitoring the energy flow throughout the network and identifying the generator which injects the energy into the network as the source. Both of [45, 46] and [47] proved that the energy dissipation is consistent with the damping torque under some assumptions and the source can be identified as the component producing energy, which means a negative contribution to the damping. The energy function for generators based on the Port-Controlled Hamiltonian theory is established in [48] which can consider the excitation system and governor models. Then, a location method based on this energy is proposed in [49] by monitoring the energy injected to the network at each port and identifying the port with positive energy injection as the source. However, it is discovered that the location result from the energy based methods may be significantly affected by the load model [50], or even misleading [51]. Another phenomenon called the concentric relaxation is introduced in [51] for power systems under forced oscillations, which could help avoid the erroneous location results. To date, this category of methods has been largely applied to power systems in the past five years [52–63].

The energy based methods are capable of identifying generator-type oscillation source since the energy dissipation is proved to be consistent with the damping toque. When applying the energy based methods to monitor the energy flows on branches in the network, the directions of the energy flows may be significantly affected by nearby loads such that the results may be misjudged. However, how to utilize the characteristics of the oscillations, such as the concentric relaxation phenomenon for forced oscillation, to accurately and reliably locate the source still needs more investigations.

7 Other methods

Besides the above methods, several other methods are briefly summarized in this section. The equivalent circuit based method in 7.1 is derived from the energy method, which provides another representation of the system under oscillations. The rest of the methods in 7.2-7.5 either depend on the system model or cannot provide a clear location of the oscillation source, which makes them less practical.

7.1 Equivalent circuit based method

An “equivalent circuit” representation for power systems under oscillations is proposed in [64, 65], which adopts the phasor concept for the deviations of power and frequency, and the “source” in the “circuit” is identified as the source of the oscillation.

7.2 Hybrid simulation based method

A hybrid dynamic simulation method is proposed in [66, 67] to locate the oscillation source, which is based on both the system model and the measurement data. The location idea is to first replace part of the differential and algebraic variables, say V_p, with known measurements and perform the time domain simulation for the rest of the variables, say V_r. If the difference between the simulated response and the corresponding measurement data for V_r is larger than a pre-designed threshold, the source is identified to be within the area associated with V_r. Repeating the process will provide a more accurate location for the source.

7.3 Artificial intelligence (AI) based method

An AI based method is proposed in [68] to locate the source of forced oscillation. Based on different operating conditions, the Characteristic ELLipsoid (CELL) is used to offline train a decision tree considering the sources respectively added to different generators or loads. Then, monitoring the parameters of the CELL using PMU measurements can help locate the source of the forced oscillation.

7.4 Graph-theoretic based method

A graph-theoretic and measurement-based method is proposed in [69] for locating the input disturbance in large networked dynamic systems. This method first applies a system identification routine to construct the input-output transfer matrix and calculate the array of nominal localization keys. Then, an estimated localization key from local

PMU measurements can be obtained for the corresponding local area. Comparing the estimated key with the nominal keys will indicate the location of the source.

7.5 Generalized linear model based method

This location method is reported in [70, 71]. Firstly, a generalized linear model for the system is fitted using the measurement data. Then, such fitted model may help determine variables that have significant effects on mode damping, which might be related to the oscillation source.

8 Discussions and conclusion

A summary of reviewed location methods is provided in Table 1. It can be seen that there is a significant gap between the current available methods in the literature and the desired location method mentioned in the introduction section. This section will point out some critical trends and challenges to the development of the oscillation source location problem and then provide a general scheme on how to make use of current available methods in practice.

Table 1 Summary of reviewed location methods

Category	Key idea	Advantages	Disadvantages	References
Traveling wave	The closer to the source, the earlier the location will exhibit oscillations	Fast	Inaccurate and unreliable detection of oscillation arrival time. Unavailability of the wave speed map in real-time. A lack of investigations for multi-mode oscillation cases.	[19–24]
Damping torque	The generator with a negative damping torque coefficient is the source	Clear physical meaning; allows for distributed implementation	Possible unavailability of rotor angle and speed data. Possible failure under forced oscillation cases.	[31, 32]
Mode shape	Largest magnitude, most leading phase of the mode shape or their combinations may indicate the source	Can deal with multi-mode oscillations	A lack of theoretical foundation. Possible failure for weakly damped/undamped oscillation and forced oscillation cases.	[35–38]
Energy	The device producing dissipation energy is the source	Allows for distributed implementation	Too strong assumptions used for modeling loads and the network.	[44–63]
Equivalent circuit	The source of the equivalent circuit is the source of the oscillation	Could be linked to energy based method	Possible failure when phasor concept cannot be applied, e.g. non-sinusoidal oscillations. A lack of theoretical investigation for multi-mode oscillation cases.	[64, 65]
Hybrid	A larger difference between model-based simulations and measurements indicates the source	Not limited to the level of the model detail	Possible unavailability of accurate model of the entire system.	[66, 67]
AI	An offline trained decision tree from model-based simulations may use online measurements to locate the source	Fast	Possible unavailability of accurate model of the entire system. Can be only applied to forced oscillation cases.	[68]
Graph theoretic method	Comparing the locally estimated key (from local measurements) and the centralized nominal keys (from model) gives the source.	Distributed implementation	Model-based partition of the whole system into areas is required and the source is only located down to the area level.	[69]
Generalized linear model	Based on an identified generalized linear model, some significant variables having contributions to the mode dynamics may be related to the source	Can find the state variables related to the source	No source location is clearly indicated	[70, 71]

8.1 Trends and challenges

1) Definition and characterization of the source

Although lots of researchers and technical papers tried to address the oscillation source location problem, a clear mathematical definition and characterization of the oscillation source are still missing.

The difficulty in the definition may be due to the various or unknown causes of oscillations such that different sources may possibly have different mathematical models. However, investigations in this direction play an important role, which could be the common foundation for all location methods even based on different principles.

The intrinsic characterizations of the oscillation source have not been paid enough attentions to so far. Different methods use different criteria to characterize their sources. For instance, damping torque based methods characterize the source by the generator with a negative damping torque coefficient, and the energy based methods characterize the source as the generator producing dissipating energy. However, we cannot prove that the generator having positive damping torque coefficient will never be the oscillation source in any way, so the damping torque based methods may possibly give wrong location results [33]. A similar conclusion holds for other methods.

Thus, future research should include the rigorous definition of the oscillation source and its accurate characterization along with the conditions under which the definition and characterization are valid.

As most studies do, the linear analysis is usually adopted to analyze the sustained oscillations and in forced oscillation cases the injection signal is usually assumed to follow the sinusoidal waveform. However, these might not always be true. In reality, nonlinearity may possibly be presented. In the forced oscillation cases, the injection signal may possibly follow certain non-sinusoidal waveforms, e.g. rectangular or sawtooth, which should have different characteristics from electromechanical oscillation [72, 73]. Thus, future research topics should address these issues.

2) Need for measurement-based methods

Traditional model-based analyses cannot help much on the location problem until (i) the system dynamic model is accurate enough and (ii) the unknown source is also accurately modeled. In reality, the location and nature of the source are typically unknown and cannot be modeled before located, so promising location methods for practical applications are supposed to be measurement-based. Model-based analysis is still useful for validating the mechanism of an oscillation event and the principle of a location method.

However, before applying any measurement-based method to real systems, all issues about the acquisition of measurements should be considered in future research to check the performance of the method. Noise in the measurements should always be considered. Besides, if a measurement-based method is implemented in a centralized way, then issues from the communication such as the loss of synchronization of data and missing data should be considered. For methods designed for online applications, time delay should also be considered.

In addition, the capability of distributed implementation of a measurement-based method is also desired and should be a direction of future research. This capability will make the method to be free of communication issues.

In today's network, the measurement devices are usually not enough to reach a full observability of the entire system states. Thus, it is desired that a measurement-based method can also provide useful information based on measurements with only partial observability.

3) Capability assessment of location methods

Almost every location method was only tested with a few specifically designed cases to demonstrate its effectiveness when proposed. It could still be possible that the method may fail for some other cases, which are not included in the published papers.

It is difficult to guarantee that all possible situations are tested when evaluating a location method. However, it is always feasible to test all imaginable situations. To this end, the development of a test cases library is a need. A library for this purpose was proposed in [33], which contains 23 oscillation cases including 14 forced oscillation cases and 9 natural oscillation cases. Although many situations have been included in that library, other situations may probably exist and should be added in future, e.g. sustained oscillation cases with constantly changing system operating conditions, and forced oscillation cases where the external force is added to other signals in the excitation system or added to other control devices. In addition, this library only has generators represented by the classical model or round rotor model and all loads are in constant power model. Although most models there are representative, they can still be different from real systems. Therefore, any devices that exist in real systems and may cause oscillations, e.g. HVDC, wind turbine and other FACTs devices, should be considered to create additional cases to supplement the library in future.

8.2 A general scheme for practical applications

To give a possible solution to the oscillation source location problem faced by today's system operators and analysts, the following provides a general scheme using all available location methods and the latest test cases library. Other schemes can be created similarly by using other criteria to categorize the available location methods.

Generally, by testing all cases in the test cases library, any location method can always be categorized into one of the three types below:

(1) Type-1: the methods whose location results are always correct but there could possibly be no location result found by the methods.
(2) Type-2: the methods that may provide multiple location results while the actual source is always included.
(3) Type-3: the methods whose location results may possibly miss the actual source and give wrong results.

This paper does not provide the categorization result of the reviewed methods, since there could be different configurations even for the same location method which will lead to different location performances.

After categorizing the location methods according to the above three types, system operators and analysts can make use of the Type-1 and Type-2 methods to locate the source or a few candidates of the source. Note that if all available methods fall into Type-3, then the oscillation source location problem cannot be solved by today's techniques even for ideally simulated cases. In such a case, there is no confident way that the system operators can follow to tackle the problem. They may rely on their experience or certain existing guidelines, or find some hints from the location results of Type-3 methods.

When a sustained oscillation event happens and one or several candidates of the source are found by the Type-1 and Type-2 methods, verification procedures should be enabled for each of the source candidates. The development of the verification procedures are also a future research topic, which may include but not limited to: (i) re-check the presence of the oscillation after eliminating a certain source candidate; (ii) use internal measurements of a certain source candidate, if available, to find the possible cause of the oscillation, e.g. detailed field investigations in a suspicious plant or substation. If the actual cause can be found and it is consistent with the location result, then the source is correctly located. Otherwise, the oscillation event under study is not included in the library. In this situation, additional cases should be designed and added to the library to represent such oscillation event. Finally, all Type-1 and Type-2 location methods should re-categorized by the updated library for future use.

With Type-1 and Type-2 location methods and the test cases library, the above scheme for locating the oscillation source in practice should work in an iterative way: new location methods can be added when available and the test cases library can be updated by adding more cases that were not included.

8.3 Conclusion

This paper summarizes the methods for locating the oscillation source in power systems. The advantages and disadvantages of each method are analyzed. Some development trends and challenges are pointed out, including a few future research topics. A general scheme for locating the source of oscillation in practice is provided and analyzed.

To conclude, more efforts on the investigations and developments of oscillation source location methods will be constantly needed.

Acknowledgment This work was supported by the NSF CURENT Engineering Research Center (No. EEC-1041877).

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