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Identifying Sources of Oscillations Using Wide Area Measurements

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SUMMARY

Synchrophasor measurement and dynamics analysis applications expose stability issues that were previously unseen. This provides valuable information and warnings, but it can be challenging to translate a warning on oscillatory stability to a specific, targeted action. Oscillations often involve many generators in a power system, and sometimes the entire system. To achieve a targeted action plan for use in operations and planning, it is necessary to locate the most significant contributions to the mode. This paper presents a novel approach to locate the area of the grid where the stability of the mode is degraded, using a practical set of synchrophasor data achievable with presently installed measurements, and not relying on a model. The approach is equally applicable in small power systems or large interconnections where a high-level identification is needed on whether there is a contribution within the system operator or co-ordinator's area of responsibility. With this information, the stability issues and warnings identified can be addressed practically and the risks reduced.

This paper describes the oscillation source location method using wide area measurements and illustrates its use in practical examples. By identifying which measurements are closest to the source of stability degradation, the problem is focused on a small area of the grid. The method is suitable for application in real-time monitoring and operational procedures, as well as post event analysis and control system tuning. The method uses the relationship between the phase of oscillations and relative damping contribution, and the changes in mode phase coincident with damping changes. A small number of voltage phasor measurements covering the whole system is sufficient to identify the region containing the source. An example of the approach is given, from a real event observed in ISO New England's area of supervision. In this case, the location identified using phase analysis is consistent with the onset of large oscillations compared to the rest of the system.

KEYWORDS

Power system oscillations, oscillation source location, damping, syncrophasors, WAMS.

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1. INTRODUCTION

Power system oscillations are a complex phenomenon involving many interacting plant. In many cases simulation results can be different from real system behaviour. A well-known example is the unstable oscillations which lead to the WECC 1996 blackout, that were not reflected in the dynamic model at that time. Significant effort was expended to modify the model, in order to reproduce the unstable oscillations leading to the blackout [1]. However, some of the challenges in managing stability are inherently very difficult to address analytically, for example, representing control system malfunction or misconfiguration, and the dynamic behaviour of loads.

Measurement based oscillation monitoring using Wide Area Monitoring Systems (WAMS) has been used to complement dynamic modelling [2]. This has proved to be a valuable application of WAMS, which has been used in operational control rooms. In cases where there are well-known modes of oscillation with behaviour and sensitivities that are understood, the system operator can design rules to mitigate the risk of degraded damping progressing to instability. However, the widespread deployment of WAMS and dynamics monitoring applications has exposed several stability issues that were not expected. In such cases, it can be very challenging to identify the source of a change in behaviour of a mode, and link the warning to an effective action. Not only is it difficult to design an operational rule for such cases, it is also difficult to identify the generator(s) where investigation and control tuning are most appropriate.

A method to identify the source of an oscillation is therefore very valuable to determine a course of action to resolve an observed degradation of stability. If the source can be identified using measurements, this enables a real-time dispatch response to move the generator away from the active/reactive power setpoint in which the damping problem occurs. Furthermore, it focuses the analysis and design effort towards a particular generator, avoiding the need for widespread field testing and model validation.

Previous work has been done on oscillation source location. Energy based oscillation source location methods require power measurements on branches in order to trace the flow of energy to the source [3, 4]. This approach requires the condition of constant undamped oscillations, and therefore is limited in its effectiveness for identifying stable but poorly damped oscillations. The approach also relies on power measurements, and few (if any) power systems have sufficient PMU measurements for a consistent implementation of the method. Other work has focused on statistical sensitivities between SCADA measurements of the system state and the stability measures [5]. This approach resolves the observability issues as most transmission systems are fully observable by SCADA, however there are disadvantages relating to spurious correlations in a large search area, and identification in cases where there are not repeated incidences of the condition.

The method is 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 lagging phase provide more damping. When there is a change in the damping of a mode, the coincident change of phase of the oscillations at participating generators indicates where the degradation in damping has occurred. The approach can be applied using the damping and phase of oscillations derived either from ambient noise or ring-down data obtained from PMUs, and can be applied in real-time or post-event.

The method presented here relies on a much smaller number of voltage phasor measurements. It is therefore more practical to deploy because it does not require current measurements, and can yield useful results without a high density of measurements. It can be applied to damped and undamped oscillations. It is also applicable to large interconnections, where detailed SCADA data sharing is impractical and only high-level voltage phasors and frequency can be shared. The results of a single excursion of damping can be interpreted, without the repetition that a statistical method requires. The approach is therefore a significant step forward in addressing the problem of managing the stability of oscillations in power systems.

2. DETAILED DESCRIPTION

The damping ratio of a mode can be seen as a result of damping contributions from different generators in the system. Some generators provide more damping than others and this can be seen from the phase of the oscillations. The objective is to identify the generators with the smallest damping contribution, as being the source of the oscillation.

2.1 Phase of Angle, Speed and Power Oscillations

First we look at the phase relationships within one generator. The swing equation that can be used to describe a generator as a second order system is shown below

$$\ddot{\delta} = \frac{1}{2H}(P_m - P_e) \qquad (1)$$

Where H is the inertia constant and P_m is the mechanical power and P_e is the electrical power.

For a mode with eigenvalue λ, the derivative leads the state by the angle of the eigenvalue. The angle of λ is given as a function of the damping ratio ζ, as follows

$$angle(\lambda) = cos^{-1}(\zeta) \qquad (2)$$

Speed leads angle by $\cos^{-1}(-\zeta)$, and acceleration leads angle by $2\cos^{-1}(-\zeta)$. For oscillations with constant mechanical power, the electrical power will be out of phase with the acceleration. As a result, electrical power leads the angle by $180° + 2\cos^{-1}(-\zeta)$. The oscillatory modes of interest have a damping ratio less than 20%. In the case of 20% damping, speed leads angle and power by 90±12°.

Figure 1 shows a phasor representation of power, angle and speed oscillations, for undamped, positively damped, and negatively damped modes.

Power can be broken into two components, one in phase with angle and one in phase with speed. A positive component in phase with speed causes damping, while a negative component causes negative damping. This can be seen from the equation of a damped second order system where the damping term is in phase with the first derivative.

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = 0 \qquad (3)$$

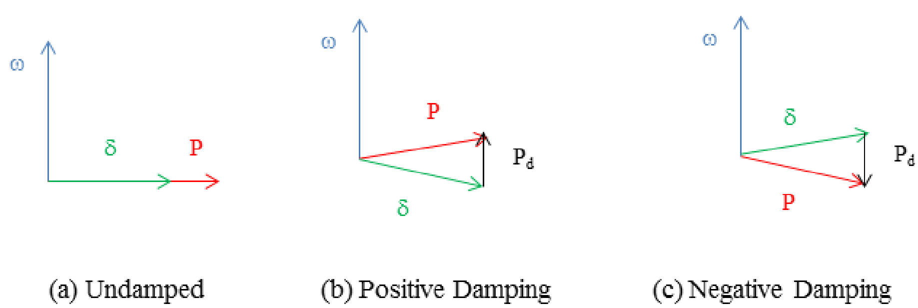


Figure 1 Speed, power and angle phase relations

2.2 Interaction between two generators

Power flow between two generators is proportional to the angle difference. A movement of angle at one generator will cause power flow changes at all generators. This can be expressed in equation (4) below.

$$c_{ij} = \frac{\partial p_j}{\partial \delta_i} \qquad (4)$$

where c_{ij} is the partial derivative of the power output of generator *j* with reference to the angle of generator *i*.

An angle increase at generator *i* will cause a power increase at generator *i* and a power reduction at all other generators. Therefore, c_{ij} is negative for $i \neq j$, and positive for $i=j$. The power change at generator *j* due to an angle oscillation at generator *i*, results in a power component which could cause positive or negative damping depending on whether it is in phase or out of phase with the speed at generator *j*.

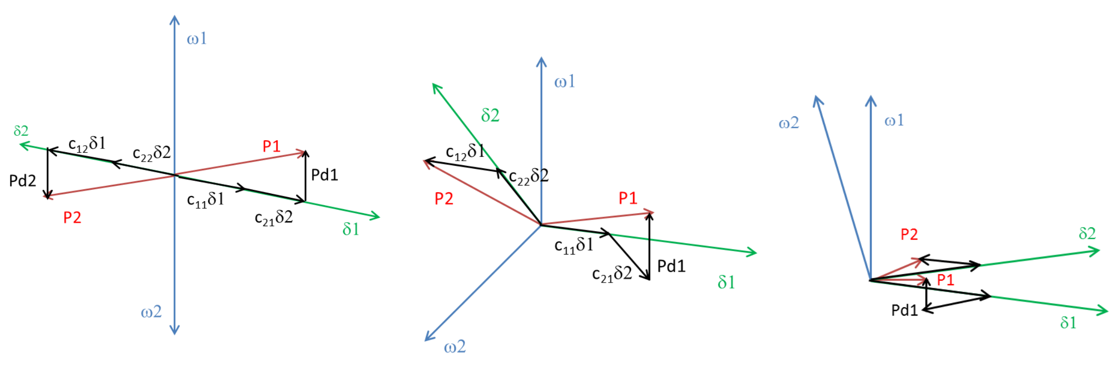
First, consider two identical machines with opposing oscillations. The phase difference between the oscillations at the two machines is exactly 180° as shown in Figure 2 (a). Power flow due to angle difference is in phase with the generator angles. A similar relationship can be obtained for two generators oscillating in phase, where all phase differences are zero.

For two generators with different damping contributions, the phase relations between power, angle, and speed at each generator are determined by the damping ratio of the mode and are the same. However, the phase shift between the two generators can be different.

Figure 2 (b) shows the phase relationships when generator 1 is providing positive damping, and generator 2 is not providing any damping, i.e., $P_{d1}>0$ and $P_{d2}=0$. In this case, the electrical power due to the angle difference (δ_1-δ_2) has a component which is not in phase with the angles. The angle oscillations at δ_1 result in a power component at generator 2 which is in phase with the speed (a damping power), while the angle oscillation δ_2 causes a power component at generator 1 which is out of phase with speed (negative damping).

The damping could be considered as two parts, an internal part provided by the generator itself P_d, and another part due to angle oscillations at other generators. In this case generator 2 gets damping power from the network, due to angle oscillations at generator1, while generator 1 gets negative damping power due to oscillations at generator 2.

The damping power in generator 2 as a result of generator 1 angle oscillations is proportional to $Sin(\theta_2\text{-}\theta_1)$; where θ_i is the angle of oscillations at generator *i*. The same relationship applies for generators oscillating in the same direction as shown in Figure 2 (c). It can be concluded that the generator with the least damping contribution is therefore the generator which is leading by an angle of less than 180°.



(a) Symmetrical interarea case (b) Interarea G1 providing damping (c) In-phase G1 providing damping

Figure 2 Phase of oscillation for two generators

2.3Generalization for more Generators

This can be generalized for any number of generators. The Damping Contribution of generator *i* is defined as the sum of damping powers at all generators due to angle oscillations at generator *i* and is given in equation (5) below.

$$D_i = \sum_{j=1}^{n} c_{ij} * a_i * \mathrm{Sin}(\theta_i - \theta_j) \qquad (5)$$

When all generators are providing identical damping, all D_i values are equal to zero, as phase differences are either 0 or 180°. This is considered the reference case. A positive D_i indicates that a generator *i* is providing more damping than in the reference case. A negative D_i means that generator *i* is providing less damping than the reference case. The generator with the smallest D_i is the generator providing the least internal damping (possibly negative), and is considered the source of the poor damping.

2.4 Simplifying Assumptions

The calculation of damping contributions requires knowledge of power angle sensitivities, which can be obtained from the system model. In order to eliminate model dependency, we can make some simplifying assumptions.

For opposing oscillations such as inter-area modes, generators can be divided into two opposing groups. The distances within each group are considered very small compared to the distance between the two groups. Therefore, the damping contribution of a generator is only considered to affect generators in the same group. For the interaction between groups, we treat each group as one equivalent generator and find phase difference between the two equivalent generators. Finding the source of oscillations is done in two steps.

First Step

Divide measurements between the two opposing directions of oscillation. After that, find an average phase for each group. This becomes equivalent to the two generator case. The group which is leading by less than 180° is identified as the group containing the source.

Second Step

If one of the two groups has a leading phase, we find the most leading location within this group. If the phase difference is approximately 180° and there is no clear leading group, we find the most leading location in each group. This would produce two locations of interest.

For modes without opposing oscillations step one is skipped and step 2 can be applied directly with all measurements considered in one group. This is the case with local electromechanical modes, and with most governor-frequency control modes.

3. TEST CASE

An example from ISO-NE is given here to demonstrate how the source of oscillations can be found from PMU measurements. In this example, sustained 0.9 Hz oscillations were observed for several minutes. Measurements from 39 PMUs covering the entire ISONE system were analysed.

Figure 3 shows the oscillations from four of the PMUs. It can be seen that PMU31 has significantly large amplitude of oscillation compared to the other PMUs. It can also be seen that PMU30 leads PMU19, and PMU34 is out of phase from the other locations.

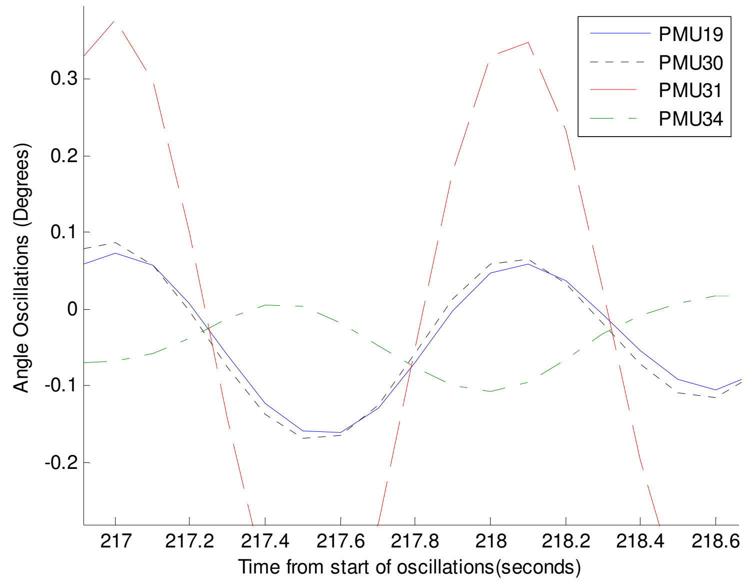


Figure 3 Time domain plot of voltage angle oscillations

The phase of the 0.9 Hz oscillations was extracted from the voltage angle measurements, and shown in compass plots. In Figure 4 (a) all arrows are of equal length and only the angle of oscillations is considered. In Figure 4 (b) the arrow lengths represent the normalised amplitude, with the largest amplitude at PMU31 equal to 1.

The measurements were divided into two opposing groups as shown in the compass plots. Group 1 is leading by approximately 150°. Within Group1, the most leading location is also the largest amplitude, which is PMU31.

This could be an obvious conclusion due to large amplitude at PMU31, which is more than three times the amplitude observed in the other measurements. However, the same location could have been identified without having PMU31. The second most leading is PMU30 which is located in the same substation at a higher voltage level. There are also cases where such amplitude differences are not observed, particularly for inter-area modes and low frequency common modes.

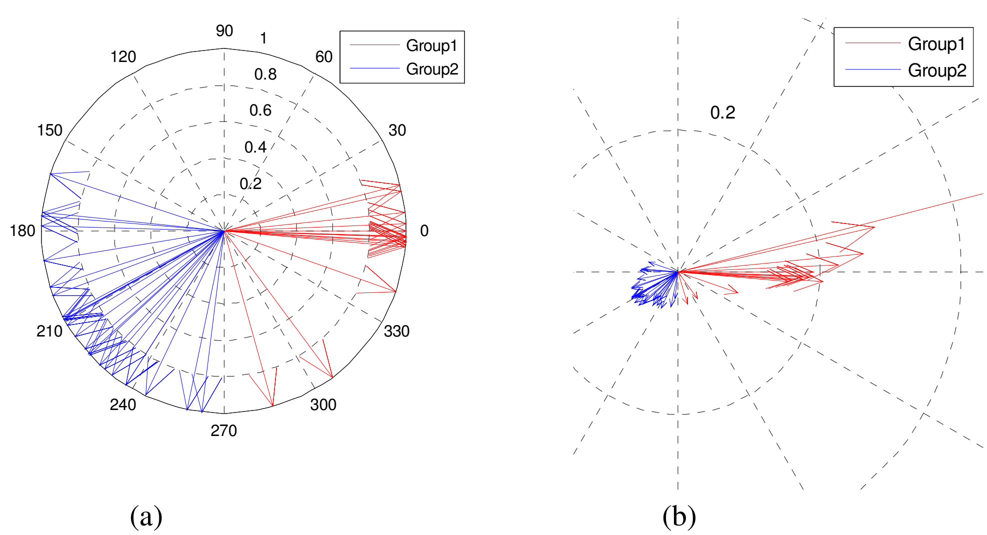
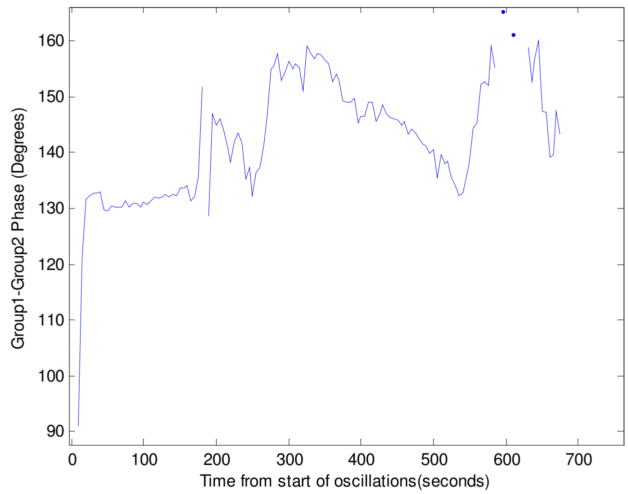


Figure 4 Compass Plots

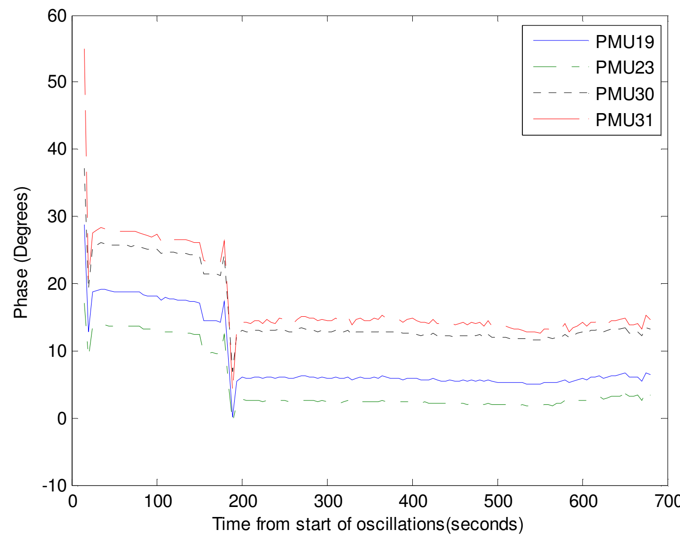
In order to demonstrate suitability for real-time applications, the analysis was carried out on 3 minute windows updated every 5 seconds. The first results are obtained after 10 seconds from the disturbance. The results are initially biased due to the large transient at the start of the event, but they become more consistent after 10 seconds. Figure 5 shows the group phase difference. During the whole period, Group1 is leading by less than 180° indicating that the source is within Group 1. The gaps in the figure are periods of time where the group phase difference could not be obtained due to the small amplitude in Group 2.



Group 1 leading by 130-150º (ie leading by <180º), indicating that less damping provided by Group 1 than Group 2.

Figure 5 Phase Difference between Groups 1 and 2

Figure 6 shows the phase results for the most leading 4 locations within Group 1. These 4 locations are in the same geographic region, and were the most leading in Group 1 during the whole period of the event. It can also be seen that the order from most leading to least leading for these 4 locations is consistent through the whole period of analysis.



Within Group 1, PMU31 is consistently leading, indicating that less damping is provided (or negative damping) by generation near PMU31.

If PMU31 was not available, PMU30 would be indicated, which is located close to PMU31, but showing much lower mode amplitude. A correct conclusion would be reached without PMU31.

Figure 6 Phase Difference for the most leading four locations

These results show that useful information can be obtained within a short period of time allowing for real-time applications.

4. APPLICATION TO A LARGE INTERCONNECTION

In a large interconnection, there may be several system operators and security co-ordinators responsible for the operation of the system, as is the case in the North American Eastern Interconnection and the European ENTSOE (continental) system. There can be several modes of oscillation over a wide area, crossing the boundaries of responsibility. In this situation, a system operator or co-ordinator has an interest in knowing whether there is a significant contribution within the area of responsibility. If there is a contribution in the region, then more detail is required to diagnose the problem, while if the contribution is outside, then it is sufficient to know that the problem is best addressed by another grid stakeholder.

The source location approach described in this paper could be applied to a large interconnection by sharing a high-level set of voltage phasor measurements. This sharing is already feasible, and would require much fewer phasor measurements than those already installed in Europe and North America. Also, the data shared is not commercially sensitive, as it does not contain power information that would reveal generation market participation. The operator can combine a high-level interconnection-wide observation of oscillations with a detailed identification of sources arising within its own region. Thus, the previously challenging issue of addressing poorly damped modes involving several operators can be resolved with this approach.

5. CONCLUSIONS

A measurement based oscillation source location method has been described that identifies the relative influences of damping between generators oscillating in the same coherent group, or in opposing phase. The method is based on analysing differences in damping contributions at different locations. The phase of oscillation is used to identify which locations contribute less damping and are identified as the source. The phase of oscillations can be extracted from PMU voltage measurements.

The method was applied to an example from ISO-NE. The phase results indicate that the source is the location with the largest oscillations. In this case, the selected location was an obvious suspect due to the significant amplitude near the source. However, it was shown that a correct conclusion would be reached even if the largest amplitude measurement was not part of the measurement set. The approach applies to both damped and undamped oscillations, and in cases where amplitude would not lead to the correct conclusion.

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