# Visualization of Large-Scale Electric Grid Oscillation Modes


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***Abstract*— Understanding the dynamics of a power system requires that information be presented in a meaningful way. Large-scale modal results are presented for a large interconnected power system using visualization methods to reveal the underlying oscillations in the system. Visualization tools are used to capture the quality of mode estimation among several bus signals, identify different modal interactions existing in the system and visualize modal power flows for tracking sources of grid oscillations. The use of wide-area visualization in a synthetic large interconnected power grid is used to uncover critical information about the dynamic state of the system, which would have otherwise, not been captured from a graphical plot of the time-varying signals.**



***Index Terms*— visualization, oscillations, wide area monitoring, power system dynamics, modal analysis**


## I. Introduction

Inherent in large interconnected power systems are characteristic, low frequency electromechanical oscillation modes which are related to load and generation variations or interactions among grid components. Faults and malfunctioning of equipment occur on the system, and can lead to excitation of these low frequency modes. The operational state of the system is threatened if the accompanying disturbances are not adequately damped or the oscillation sources identified and eliminated. Hence, oscillation monitoring and effective control actions are critical activities for power engineers in their bid to preserve the safe and secure operation of the grid. In the era of high resolution measurement devices, more power system data are now made available to engineers and system operators in order to gain a better understanding of the behavior of the system. As a result, there is a need to provide additional ways to convey system dynamics information to users [1].

Continous advancements in computer processors and graphics imaging prompts the deployment and use of high-end computer machines in modern power control centers. Consequently, large amounts of power grid information are now being presented more effectively and within shorter processing times. Visualization tools have made use of contour maps, dynamic objects, animations and movies to present information about system voltage, frequency, transmission line power flows and other dynamic grid information [2]-[7]. Reference [8] makes use of phasor diagrams and animation to identify coherent group formations and mode shape of a specified inter-area mode at spatially distributed system nodes respectively. Using a combination of 2-D and 3-D graphs, phasor diagram and data table, [9] reports grid modal information. Spatial and temporal variation of mode amplitudes are presented in [10]. These methods are often able to provide oscillation information on a nodal or limited area basis. However, it is more critical for engineers to create a mental picture of the global state of a system when monitoring the evolution of grid trends and dynamics. As power systems increase in size, this ability to create a holistic system perspective is impaired, thus losing track of system-level activities.

The objective of this paper is to address these limitations by presenting modal results obtained from the analysis of a large, interconnected system in a manner that is able to convey wide area information about grid dynamics to a user with the aid of an expanded suite of more effective visualization tools. The goal is to assist power engineers to make better informed decisions. An information layering technique through the use of geographic data view objects and contouring is used to present large amounts of modal and other processed results [11]-[13]. Information pertaining to the quality of mode estimation technique, wide-area oscillation mode activities, and source of oscillations are used to characterize the system dynamics. Since the focus of this paper is on improving grid awareness through wide-area visualization, the authors have made use of a matrix pencil technique, for the reasons stated in the next section and as mentioned by [14], to extract mode information from power system measurements.

## II. A Brief Background on Modal Analysis Techniques

This section briefly describes some of the different techniques that have been used in power systems to reveal the underlying low frequency signals in power system measurements. Complete details of these techniques can be obtained from the literature [14]-[19].

Given an observed time-varying measurement, $y(t)$, the goal of modal analysis is to obtain a re-constructed signal $\hat{y}(t)$ that is a sum of (un)damped sinusoids, and as shown in (1).

$$\hat{y}(t) = \sum_{j=1}^{q} A_j e^{\sigma_j t} \cos(\omega_j t + \phi_j) \quad (1)$$


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The $j^{th}$ mode is characterized by the modal parameters: damping factor ($\sigma_j$), frequency ($\omega_j$) and mode shape consisting of amplitude ($A_j$) and phase ($\phi_j$) . The number of modes is given by $q$. The error between the original and reconstructed signal, $e(t)$ is computed using (2).

$$e(t) = \sum_{j=1}^{q} \left\| y(t_j) - \hat{y}(t_j) \right\|_2^2 \quad (2)$$

Different techniques have been proposed for use in power systems to reveal the underlying low frequency signals intrinsic to power system measurements. The traditional Prony analysis computes the roots of a polynomial to determine the modal frequencies of a signal. These characteristic polynomials are associated with a discrete linear prediction model (LPM) which are used to fit the observed measurements [15], [16]. In the matrix pencil technique, a singular value decomposition is performed on a Hankel matrix, after which the eigenvalues and other modal parameters are obtained [17], [18]. One of the advantages of this method is its tolerance to the presence of noise in the observed measurements. A nonlinear least squares optimization method, which encapsulates the linear variables into nonlinear variables, is used by the variable projection method (VPM) to simultaneously estimate all the modal parameters [19]. However, reference [14] showed that often times the initial modes provided by the matrix pencil method are sufficient. Also, a fast method of dynamic mode decomposition was proposed in [10] for off-line and on-line simultaneous processing of multiple time-series signals.

The above-mentioned modal analysis techniques are able to estimate the modal content of power system oscillatory disturbance data. In a system with a large number of signal measurements, obtaining system-wide, dominant oscillation modes, and still generating re-constructed signals considered to still be close approximate to the actual signals within reasonable computation times can be a challenging task. As a result, in this paper, an improved matrix pencil method which iteratively minimizes the error in (2), is proposed in order to detemine the low frequency signals in a data set. The technique uses a subset of the signals to calculate the modes after which the reconstructed signals are calculated for the observed measurements. If a system comprised of $n$ number of time-series signals, the system modes can be approximated using $m$ multiple signals obtained using heuristic methods such that $1 \leq m \leq n$. For every signal added to the subset, a signal reconstruction is carried out for all $n$ original measurements. A good choice of $m$ balances between the computation time and better capturing dominant modes across the system.

The focus of this paper is on mode visualization, and does not dwell on the method used to identify these low frequency signals in power system measurements. However, the results in this paper will always be applicable regardless of the chosen method. The mode decomposition generates different component frequency and damping values. Associated with each of these components are the mode shape and reconstructed signal $\hat{y}(t)$ for each observed measurement. In addition, processed data are obtained from the computation of individual transmission line power flows used for the detection of oscillation sources.

## III. Wide Area Visualization of Mode Information

In this section, the test power system used to generate synthetic data used in this work is presented. Upon modal decomposition, modal results extracted from these transient stability data for a specified contingency event are presented using visualization methods. The presented information includes quality of the mode estimation and the wide-area mode activity at signal bus locations.

### *A. Test Case*

The test case used in this paper is a 10,000 bus synthetic power system covering the Western part of the United States [20],[21], and whose one-line diagram is shown in Fig. 1. It uses transient stability model parameters which have been tuned to ensure that system dynamics are close to real-life scenarios. Transient stability studies carried out on the system are used to generate 10-second data for two different contingency events. Event C1 is the identifier for a contingency involving the outage of five largest generators, and C2 identifies the same contingencies in C1, but with 19 generator power stabilizers deactivated. These stabilizers were disabled for the purpose of generating a case scenario with significant inter-area system oscillations. For the modified modal analysis process, the $m$ value was set to 20. This was based on the short duration execution time, and the ability to still obtain reconstructed signals observed to closely approximate their corresponding original measurements.

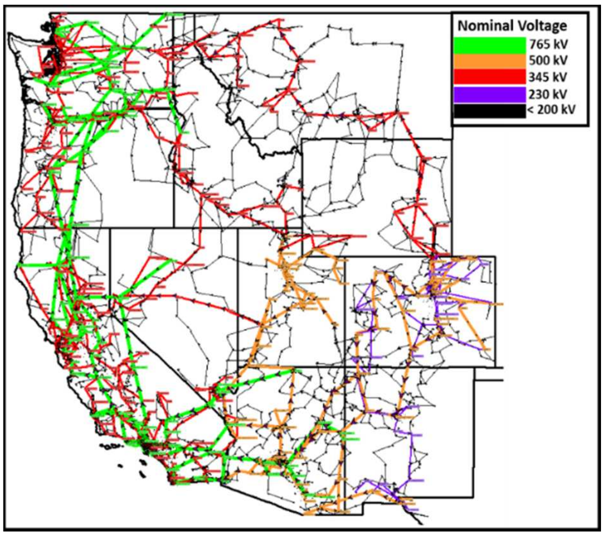


Fig.1. A 10,000-bus synthetic interconnected grid comprising 4,762 substations

The wide-area display of results from the 10,000 bus system is based on a pre-existing one-line diagram of the system over laid on a geographical map of the western United States. In addition to contour plots, dynamic data can be visualized using geographical data views (GDVs) [13]. This enables user customization of a display in order to see power system quantities by making use graphical objects. Information is encoded using the attributes of object color, size, rotation or shape.

### *B. Quality of Mode Estimation*

Here the desire is to approximate as closely as possible each original signal using the signals from (1). However, the few dominant system modes are not sufficient to fully represent the original signal and other dynamics in the system. The quality of the mode estimation process is thus measured in terms of the difference between the original and reconstructed signal. This is known as the cost or error function.

Equation (3) shows an average error method ($\varepsilon$) that has been used to compute the cost function.

$$\varepsilon = \sum_{i=1}^{\alpha} \frac{|y(i) - \hat{y}(i)|}{\alpha} \tag{3}$$

The total absolute error over the different time points is averaged over the number of samples ($\alpha$) in order to ignore the effect of the length of the reproduced signal.

Fig. 2 shows the reproduced and original voltage signals for the best and worst cases, and which were identified at buses 60449 and 50382 respectively after the C1 event.

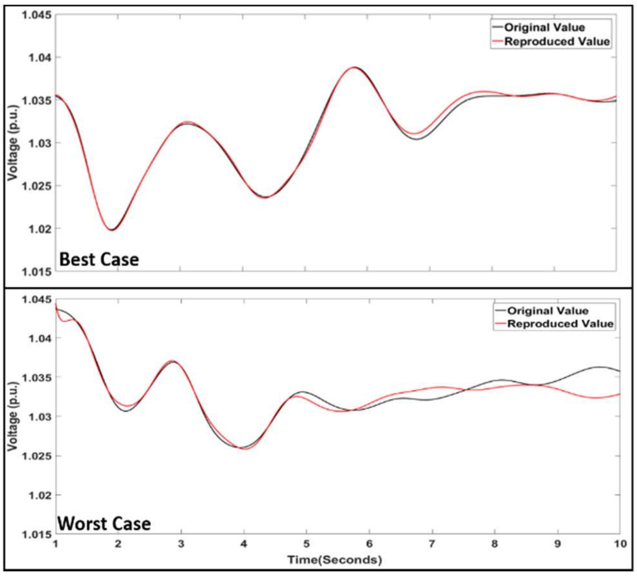


Fig.2. Best and worst cases for reproduced signals

Using (3), the computed mismatches for the best and worst cases are 0.0094 and 0.0356 respectively. From the figure, the best and worst cases indicate the ability of the modal technique to capture the dominant low frequency modes which characterize the system oscillations. This is observed by the near-matching of the original and reproduced signals. A good match is also observed for the other signals in the system.

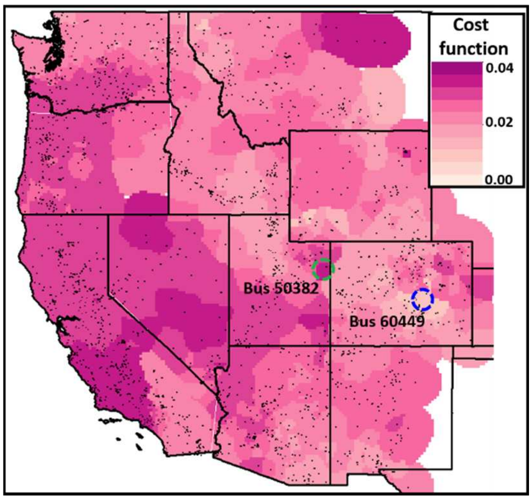


Fig.3. Wide –area system cost function

Wide-area trend in the system cost function is shown in Fig. 3. The color scale has been set arbitrarily, [0, 0.04] to indicate the best and worst case matching errors while the signal buses 60449 and 50382 are enclosed by blue and green circles respectively. A wide variation of the cost functions is observed in the system as depicted in the figure, and could be attributed to the previously stated reasons. Also, since reactive power and voltage effects are known to be more localized, other non-dominant modes are not captured by the decomposition process. The wide-trend cost function in Fig. 3 provides an instant quality assessment of the modal technique used, and can also help to identify local events in the system which might not be captured by the dominant frequency modes.

### *C. Oscillation Modes and Coherent Mode Groups*

Considering the quality of the mode estimation process, the next step is to visualize the identified oscillation modes. The mode shape describes the relative activity of the state within an oscillation mode, and comprises of magnitude and angle. The vectoral attribute of this quantity can cause distraction when visualizing individual signal mode shape information in a wide area network. The use of GDV objects on contour plots to observe system wide trends can be shown to demonstrate layering techniques. Also, abrupt change in colored contours between angle limits, -180˚ and 180˚, can be misleading since in actual geometry both angles are exact. To avoid this sudden color change, a circular color map, which assigns the same or similar colors to angular values close to these limits, is used.

Applying the decomposition technique on frequency measurements obtained from the C2 event, seven different oscillation modes were identified. Fig. 4 and 5 show mode shape information for an inter-area mode (0.48 Hz) and a local mode (1.71 Hz). All signal amplitudes have been scaled by their standard deviation values.

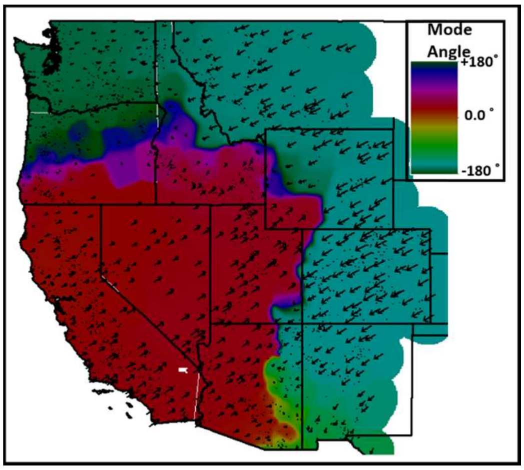


Fig.4. Frequency mode shape for 0.48 Hz component

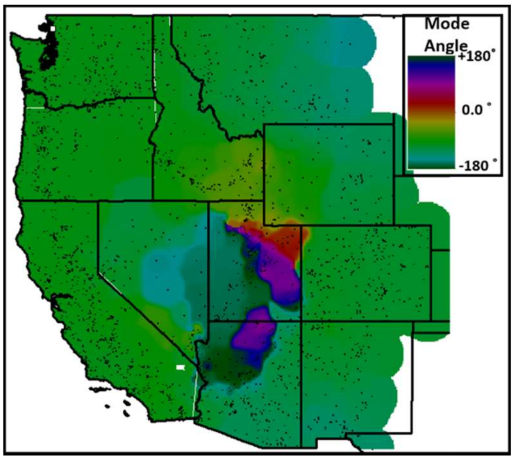


Fig.5. Frequency mode shape for 1.71 Hz component

A circular (or cyclic) color map used to highlight the mode angles at different signal bus locations provides a user with a wide-area summary of the swing direction at the different buses. Individual bus signal amplitude and angle are encoded in the size and orientation of the phasor arrow relative to the positive x-axis respectively. The geographical information of each bus is used to set the location of its GDV-based arrow. Fig. 4 and 5 show distinct areas such that buses in these regions have a similar direction of swing for the oscillation mode. When compared with the local area mode, higher levels of oscillations are observed in the inter-area mode as shown by the significant length of phasor arrows in Fig. 4. The implications of the mode shape amplitude is described in the next sections.

In understanding the key dynamic stability behavior of large interconnected systems, the interest of a user is often in the identification of modal coherent groups (e.g. for controlled islanding). Depending on the color map used in Figs. 4 and 5, a wide color spectrum of the mode shapes at the different bus locations could conceal actual system global dynamic behavior. The application of machine learning or any other similar techniques, with the ability to intelligently aggregate unidirectional bus mode shapes into smaller coherent group formations, uncovers the dynamic behavior of the system and provides further insights to the users.

Given two signals with phase angles $\phi_1$ and $\phi_2$, the angular distance ($d_{12}$) between them is computed from (4)

$$d_{12} = 1 - \cos(\phi_1 - \phi_2) \tag{4}$$

In this work, we employed a clustering technique to identify large swing clusters in order to capture the major modal coherent groups in the system. Fig. 6 and 7 show contour plots of the identified coherent modal groups after the application of a similar quality threshold clustering technique that was used by the authors in [22].

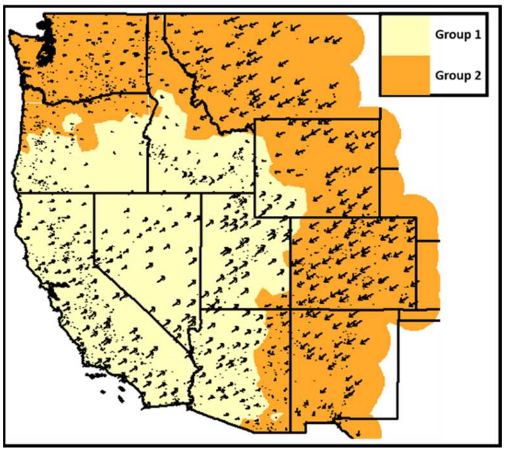


Fig.6. Frequency coherent groups for inter-area mode (0.48 Hz)

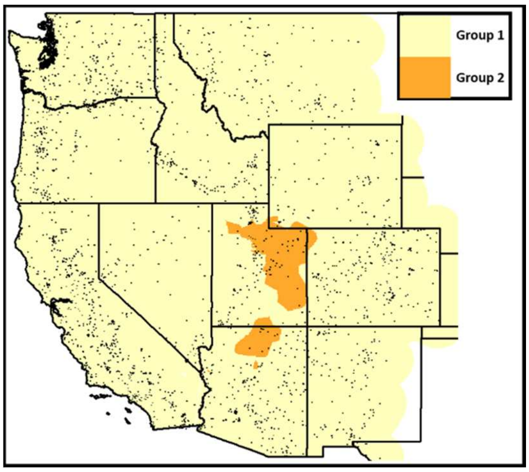


Fig.7. Frequency coherent groups for local mode (1.71 Hz)

Fig. 6 shows a dominant western-eastern, inter-area oscillation as observed by the group formations and opposing directions of signal phasor arrows in both groups. Local mode oscillation is indicated by the formation of the smaller group 2 in Fig. 7.

In summary, key dynamic system behavior and extent of mode activities can be easily captured for all identified modes in the system by clustering mode shapes and visualizing them similar to Fig. 6 and 7.

## IV. VISUALIZATION OF OSCILLATION SOURCES

Sustained oscillations pose a threat to the safe and secure state of the system, and it is important to identify oscillation sources in order to eliminate them. Different methods have been proposed to identify grid oscillation sources [23]-[25]. A simplified method motivated by the energy approach of [23] is used for locating the source of oscillations. However, modal analysis is used to replace the band-pass filtering stage. The modified approach is a robust and simplified technique used to compute the net power flow at all substation bus locations.

### *A. Oscillation Mode Power Flow*

Given a mode $j$ component obtained from using voltage angle measurements in the mode estimation process, the reconstructed signal at a bus $k$ is given by (5).

$$\theta_{k,j}(t) = A_{k,j} e^{\sigma_j t} \cos(\omega_j t + \phi_{k,j}) \tag{5}$$

At the oscillation source, it can be assumed $\sigma_j$ to equal zero, and recognize that the source also leads every other bus with a phase angle ($\phi_{k,j}$). Shifting the phase angles at all buses by $\phi_{k,j}$ so that it is zero at the bus with the largest $A_{k,j}$ value, (5) is updated to (6).

$$\theta_{k,j} = A_{k,j} \cos(\phi_{k,j}) \tag{6}$$

An approximated mode $j$ line power flow across any two buses, $m$ and $n$ is then given by (7).

$$P_{mn} \approx \frac{1}{X_{mn}} \left( A_{k,m} \cos(\phi_{k,m}) - A_{k,n} \cos(\phi_{k,n}) \right) \tag{7}$$

$X_{mn}$ is reactance of the line connecting buses $m$ and $n$. The source of the sustained oscillation is the node location with a net source of mode j power flow. Similarly, a sink will be a node with a net absorption.

### *B. Source of Local Mode Oscillation*

From the voltage angle measurements obtained from the C2 event, a dominant 0.49 Hz inter-area mode was identified. However, more significant was a 1.70 Hz local mode oscillation with a negative damping of -0.04, and indicative of a sustained disturbance. These modes correspond to those previously identified in Section III.C using frequency measurements. Implementing the steps described in (5) to (7) to identify the source of oscillation for this local mode, the net power flow computed at each substation (obtained as the aggregation of the net flow of substation buses) is visualized in Fig. 8. For ease of identification, the GDV phasor arrows and contour plots have been removed. Substation net power flows are encoded using attributes of the GDV-based oval shape – magnitude is indicated by the relative size, and the direction is represented by the color (green and red imply net injection and absorption respectively).

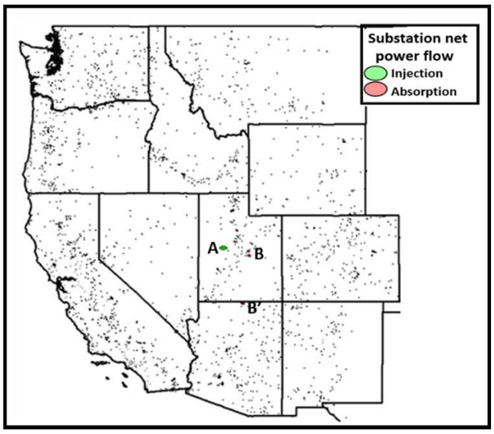


Fig.8. Substation net power flows for voltage angle 1.70 Hz local mode

Fig. 8 shows majority of the substation locations having little or no contribution to the power flows associated with this local mode. However, one is immediately able to identify the local dynamics in the Utah area where the largest power source to the 1.70 Hz mode is substation A, and with a net injection of 3.13 per unit. Among other nearby sinks are substations B and B' identified as the main sinks for the oscillation flows with a total absorption of 1.56 per unit. Fig. 9 shows the consistent outward flow pattern from substation A into B, B' and other sink locations.

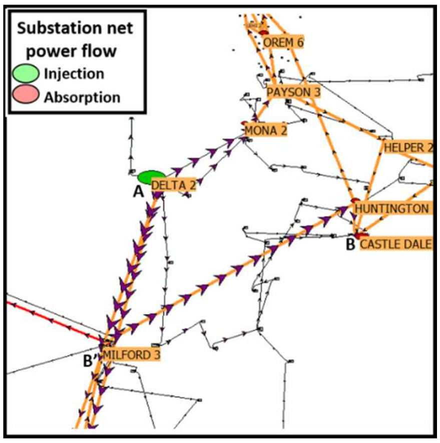


Fig.9. Mode power flows for 1.70 Hz local mode

The significant modal interaction is restricted to the large amounts of mode power flowing along the transmission lines and transformers located in this area. Currently, investigations are ongoing to determinate the actual cause of oscillation at the substation generator.

### *C. Local and Inter-area Modal Power Flows*

Inter-area oscillations are predominantly caused by weak inter-connections between different parts of the system leading to the formation of coherent groups oscillating against each other or against a part of a system.

The distributed substation net power flow in Fig. 8 showed a local concentration of mode power flows for a given local frequency component. In an inter-area mode, a complex modal interaction between areas is observed in the power flow distribution across the lines in the system.

Fig. 10 shows the net substation power flows for the 0.49 Hz inter-area mode extracted from voltage angle measurements obtained from the C2 event. The same GDV scaling factor used in Fig. 8 has been applied.

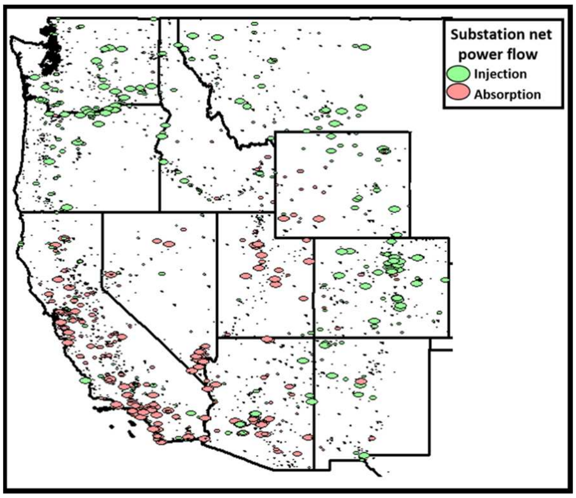


Fig.10. Substation net power flows for voltage angle 0.49 Hz inter-area mode

The boundary formed by the substation power source and sink locations indicate a net power flow between the western and eastern regions of the grid. As shown, there is a higher participation of all system substations in this mode as shown by the number and size of the oval shapes in the figure than in the local mode observed in Fig. 8. A combination of these observations indicate the complex, wide-scale modal interaction in the system due to inter-area mode oscillations.

## V. Conclusion

The dynamics associated with a large interconnected power system are revealed through the aid of wide-area visualization of modal data extracted from system measurements. Using the capabilities of GDVs and contouring tools to present and explore large data sets of results, patterns of different mode activities and location of source oscillation modes were discovered.

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