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PMU-Based Oscillation Analysis of the North American Interconnections

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SUMMARY

The increasing deployment of phasor measurement units (PMUs) across the bulk power system (BPS) is increasing the observability of the system. This increased observability provides a unique opportunity for system operators, planners, analysts and regulatory bodies to better understand the modal characteristics of the system. In this paper, a preliminary look at the modal characteristics of three interconnections in North America have been analysed – the Eastern, Western, and ERCOT Interconnections – using PMU data collected from Reliability Coordinators (RCs) for specific events. Additionally, for the same events, the modal characteristics obtained from the base case simulation models have been compared with the results from the PMU data. This comparison could be useful for benchmarking the model-based modal analysis approach with actual data; hence improving the system characteristic definition.

KEYWORDS

Modal analysis, PMU data, Non-linear least squares

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OBJECTIVE AND METHODOLOGY

Availability of high resolution time-synchronised PMU data across the interconnections in North America offers a range of possible studies using actual system event data. The value of this PMU data has been realized for system model validation, power plant model validation, and frequency response analysis at the North American Electric Reliability Corporation (NERC). Measurement-based modal analysis also offers an in-depth look into the nature of the system and how it behaves. The results from such a study can then be used as the starting point for other studies as well as providing the industry with guiding principles around the dynamic nature of each interconnection during different operating conditions.

Oscillation analysis includes detection and identification of the inter-area oscillatory modes in the system – defined by their mode shapes, mode frequencies, and mode damping ratios. Using synchronised PMU data obtained from across each interconnection for specific events, numerical modal analysis is performed in order to obtain the system modal characteristics. Traditional numerical analysis techniques generally uses a lower-order linear model to curve fit the higher order non-linear model of the actual system response [1]. The analytical methods of performing the same modal analysis would be to perform an eigenvalue analysis on the state equations representing the system and its components [2, 3]. However, in both methodologies, as a lower order linear model is being used to assess the behaviour of a highly non-linear system, one can only hope to get a best estimate of the modes present in the system.

NERC is collecting time synchronised PMU data for specific events, coordinating with the Reliability Coordinators and the NERC Synchronized Measurement Subcommittee (SMS). NERC is using this data for modal analysis as part of a Special Reliability Assessment to be published in 2017, with the intent of providing the electric utility industry with a better understanding of the fundamentals of inter-area modes as well as forced oscillations on the bulk power system (BPS). Additionally, which units or elements participate in each mode as well as where the modes are most observable can be better understood. This information helps system operators and RCs in monitoring for poorly damped inter-area oscillations or identifying forced oscillations on the system. However, it is obvious that the signals of particular units or elements, or for specific events, must be collected for the analysis to provide a comprehensive assessment. These results can further be used by the industry as part of a model validation and benchmarking exercise to test the accuracy of simulation models and analytical modal analysis approaches.

With numerous oscillation analysis tools available [4-7], it is not the intent of this paper to compare the results obtained from the various tools. Using one tool, the open source VARPRO tool [6], this paper provides insight into the preliminary analysis of inter-area oscillations in each interconnection.

USING THE VARPRO TOOL

The VARPRO tool is a MATLAB® [8] based tool which accepts data in comma separated format and uses a nonlinear least squares optimization method in the calculation of the modes. Figure 1 shows a screenshot of the main user interface. The channels tab indicates the number of data columns that have been read and are ready for analysis. The number of columns to be used for analysis can be changed as needed, but it is recommended to use multiple columns of data of the same signal type for a more accurate analysis [9]. In numerical modal analysis, the width of the analysis window and the signals selected play a significant role in the accuracy of the results. Thus, the tool allows the user to define a time window while also defining the number of modes to be solved for in the initial run of the algorithm. Once parameters are set, the algorithm is executed using the ‘Run VARPRO’ button. This opens up the execution window also shown in Figure 1. Accuracy of the curve fit can be examined visually by comparing the time domain graphs of the measured data and estimated curve fit or by comparing the Fast Fourier Transform (FFT) of both signals. Alternatively, the quantitative estimate of the accuracy of the curve fit is given by the objective value at the bottom of the window. The lower the objective value, the more accurate the curve fit. If the results are not satisfactory, the analysis can be run again using the results from this run as the initial conditions for the subsequent run. Apart from providing the mode frequencies and damping ratios, the tool also provides the mode shape plot for each mode. The mode shape plot is useful in determining interaction of individual areas or generators with each other for a particular mode. Additionally, the mode shape plot conveys the contribution of each analysed signal in the particular mode. This type of information can be useful in identifying the controllable units/components for a particular mode.

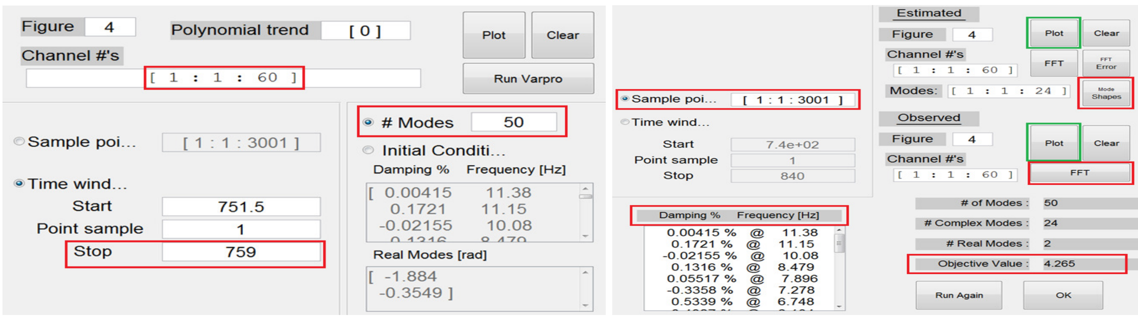

Figure 1: VARPRO Tool GUI

INTERCONNECTION ANALYSIS RESULTS

The data requests sent to the Reliability Coordinators required around 10 minutes of pre-contingency ambient data and 15 minutes of post-contingency data. The data is pre-processed prior to running the analysis to remove anomalous data such as zeroes or non-numerical values indicative of poor PMU data quality (e.g., data dropouts). Further, the number of data signals collected was vast; therefore, coherent signals were excluded and only one signal of the coherent set used. Signals were also chosen at random to ensure a wide-area view across the interconnection. The analysis and results of each interconnection are detailed below:

Western Interconnection

The event under consideration was 746 MW loss of generation in the Colorado area. The frequency around the time of occurrence of the event, plotted from the data received, is as shown in Figure 2. Modal analysis was carried out for the ringdown period following the occurrence of the event – during the first 10 seconds following the disturbance as shown in Figure 3. The large oscillatory signal was excluded from the analysis as it was located very close to the tripped generation. Among the various modes obtained from the numerical modal analysis of this event, three modes were identified as possible system characteristic modes based on frequency and damping ratio as shown in Figure 4.

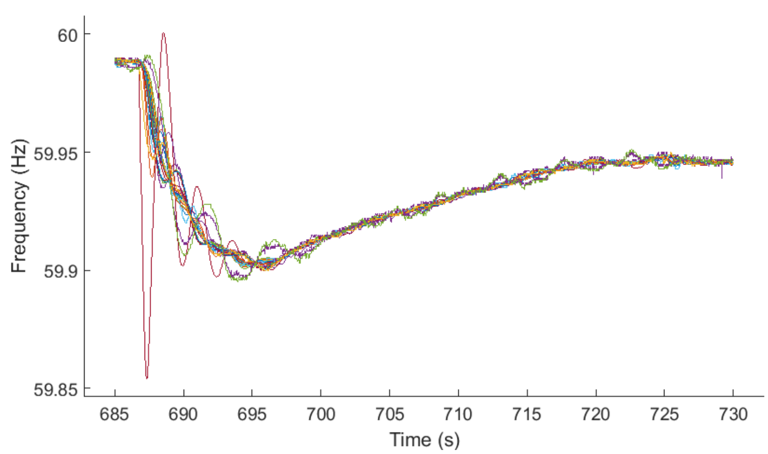

Figure 2: Western Interconnect frequency for 746 MW trip

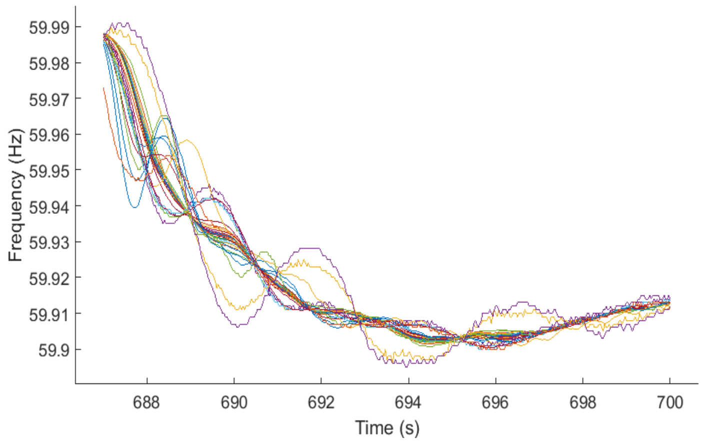

Figure 3: Ringdown for WI 746 MW trip

Freq.[Hz]		Damp.%
2.048	,	-13.18
1.138	,	33.12
0.6598	,	22.44
1.867	,	-0.5201
1.713	,	0.5085
1.505	,	-0.6663
1.391	,	4.001
1.252	,	-0.4945
0.9376	,	3.265
0.8769	,	3.765
0.7669	,	4.189
0.5544	,	8.319
0.4091	,	14.47
0.3627	,	9.769
0.06107	,	24.76
0.005424	,	99.96
0.2168	,	14.41

Figure 4: System characteristic modes

The mode shape for these three modes reflected the well-known North-South oscillation of the Western Interconnect as shown in Figure 5 for the 0.2168 Hz mode. To compare these results with the model-based simulation results, the same 746 MW trip was applied a Western Interconnection base case with similar loading as the event under consideration. The simulations were run in GE-PSLF [10] using the full Western Interconnection system models developed by WECC [11]. Figure 6 shows the frequency response observed from the simulation with comparison to that observed from the input data. The results of the numerical modal analysis performed on the simulation output is shown in Figure 7. It can be seen from the frequency response comparison that while the same trend is observed from the simulation, there is still a need to improve the simulation models.

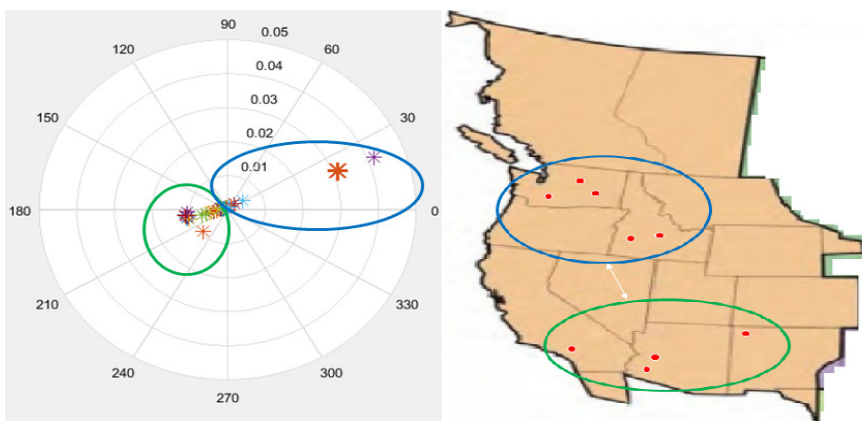

Figure 5: Mode shape for 0.2168 Hz mode of the Western Interconnect

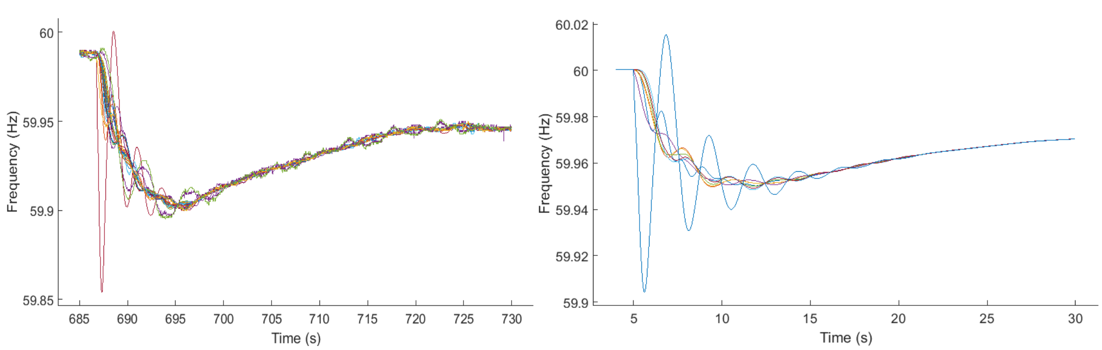

Figure 6: Measured frequency (left) compared to simulated frequency (right)

Freq. [Hz]	Damp. %
4.041 ,	0.7677
3.126 ,	0.5401
2.916 ,	0.485
2.665 ,	1.8
2.365 ,	-0.4426
2.206 ,	8.076
2.072 ,	4.041
1.863 ,	0.8406
1.673 ,	5.792
1.419 ,	12.14
1.243 ,	16.42
0.9604 ,	15
0.8165 ,	11.72
0.699 ,	8.648
0.6255 ,	9.481
0.4048 ,	15.24
0.07049 ,	98.98
0.2699 ,	14.59
0.4248 ,	7.739
0.0008286 ,	99.97

Figure 7: System characteristic modes from simulated data

The frequency domain results of the simulation closely match those obtained from the measured data with regard to the mode frequency/damping and the regions participating in the modes. However, in the time domain, though the trend is the same, it can be seen that the nadir of the frequency is different. This could be an artefact of differences between the pre disturbance operating point of the simulation base case and the measured event operating point, due to the seasonal construction of the base cases. Additionally, it could be a result of suspicious dynamic data models in the base cases. A comprehensive benchmarking exercise of the practical equipment with the simulation models would be beneficial to ensure that data quality and correctness of the simulation models.

Eastern Interconnection

The event under consideration was a 970 MW trip in the Tennessee Valley Authority area. Eight (8) seconds of ringdown portion where the inter-area modes were observable in the frequency response from the PMU data, shown in Figure 8, were used for the analysis. Results from the modal analysis with the possible system characteristic modes are shown in Figure 9.

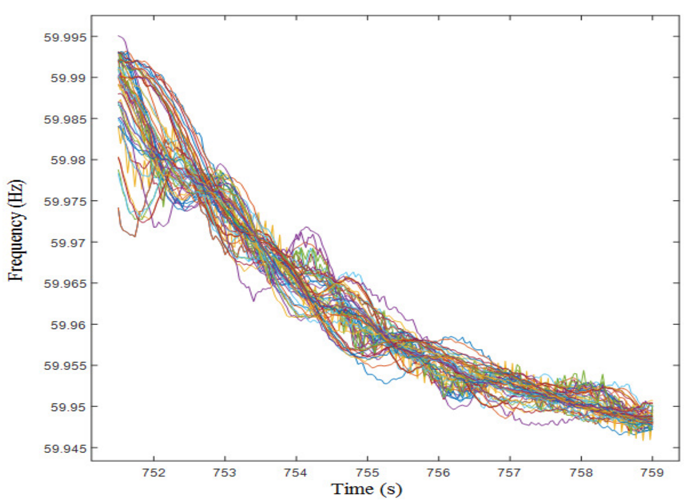

Figure 8: Ringdown for EI 970 MW trip

Freq. [Hz]	Damp. %
11.15 ,	0.1721
10.08 ,	-0.02155
8.479 ,	0.1316
7.896 ,	0.05517
7.278 ,	-0.3358
6.748 ,	0.5339
6.104 ,	0.4827
5.176 ,	0.01473
5.486 ,	1.997
4.822 ,	-0.3682
1.422 ,	83.92
4.193 ,	0.2603
3.971 ,	0.4474
3.315 ,	0.5503
1.704 ,	33.37
0.551 ,	12.05
1.54 ,	-1.654
1.147 ,	2.297
0.8876 ,	10.88
0.7303 ,	3.654
0.6555 ,	8.485
0.488 ,	5.896
0.2493 ,	11.7

Figure 9: System characteristic modes

The mode shape for the 0.25 Hz mode is as shown in Figure 10. It can be seen from the mode shape that the ISO New England area oscillates against both the Midcontinent ISO area and Southern Company area. Further, it can be seen that the mode propagates through almost all areas of the interconnection.

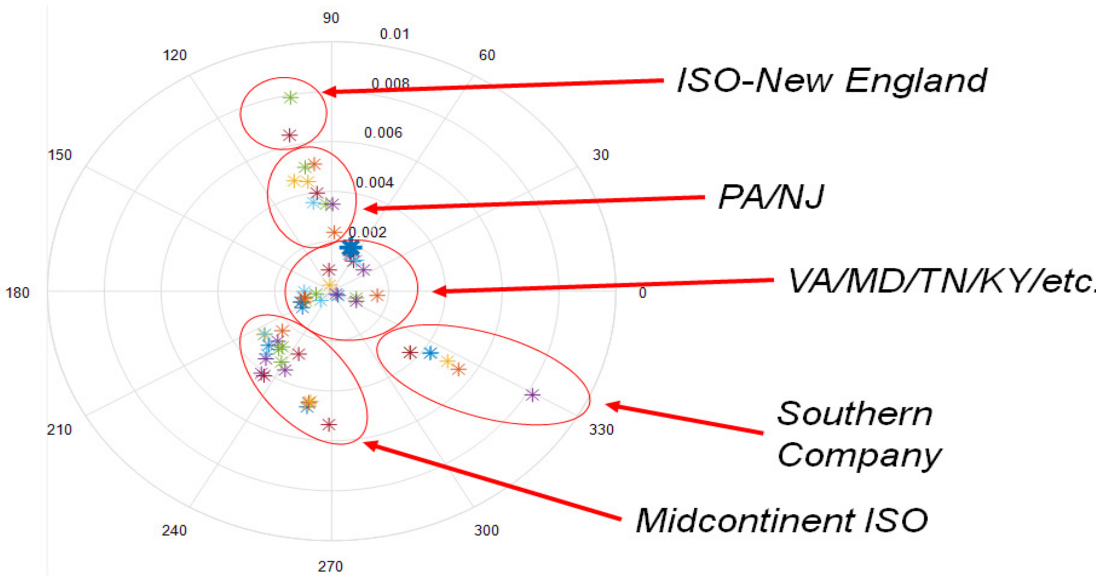

Figure 10: Mode shape for the 0.25 Hz mode of the Eastern Interconnect

Texas Interconnection

The event under consideration was a 1376 MW trip in the region. A 9 second ringdown window was considered and relative[1] frequencies were used for analysis as shown in Figure 11.

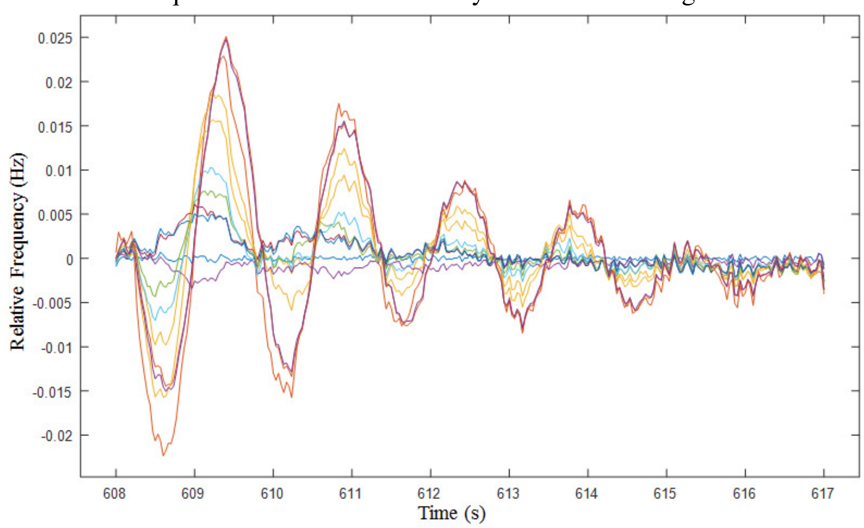

Figure 11: Relative frequency ringdown of Texas Interconnection

The possible system characteristic modes are shown in Figure 12. From the input frequency data, a mode of around 0.5 Hz can be observed and this lies in line with the two possible modes indicated in Figure 12. High-level analysis of the mode shape for this dominant mode indicates that the oscillation is between the northwest and southeast regions of the interconnection as shown in Figure 12.

[1] Inter-area oscillations are hard to visually identify using frequency measurement; therefore, relative frequencies to one PMU measurement are used to show the inter-area oscillations occurring during the event.

Freq. [Hz]	Damp. %
10.57 ,	-0.1373
9.56 ,	0.01426
9.201 ,	0.02828
8.552 ,	-0.1884
7.471 ,	-0.6868
7.208 ,	-2.764
6.691 ,	-0.07778
6.348 ,	0.2683
6.148 ,	0.6529
5.43 ,	-0.437
4.415 ,	0.6345
4.065 ,	3.021
3.455 ,	18.96
3.174 ,	2.01
0.2786 ,	98.74
2.228 ,	4.212
1.417 ,	1.355
1.121 ,	6.331
0.5996 ,	23.22
2.948e-05 ,	100
0.4552 ,	-2.751
0.8645 ,	6.431
0.6956 ,	7.207

Figure 12: Possible system characteristic modes and geographical mode shape

CONCLUSION

Widespread deployment of PMUs has provided a unique opportunity to study oscillatory behaviour of the BPS using measurement-based methods rather than relying on model-based approaches. In this paper, the modal characteristics of the Western, Eastern, and Texas Interconnections in the North America are presented using an open source numerical analysis tool. PMU data was collected from RCs, enabling centralized collection of wide-area, time-synchronised measurement data from PMUs for specific oscillatory events of interest. Results from the analysis will be formulated into an industry-wide Special Reliability Assessment on inter-area oscillations. While the analysis presented here is preliminary, it shows the presence of some well-known modes and system interactions while also revealing new characteristics. Further, the analysis supports benchmarking simulations models to improve dynamics case fidelity.

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