NERC

NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Detailed Event Analysis

July 2019

RELIABILITY | RESILIENCE | SECURITY

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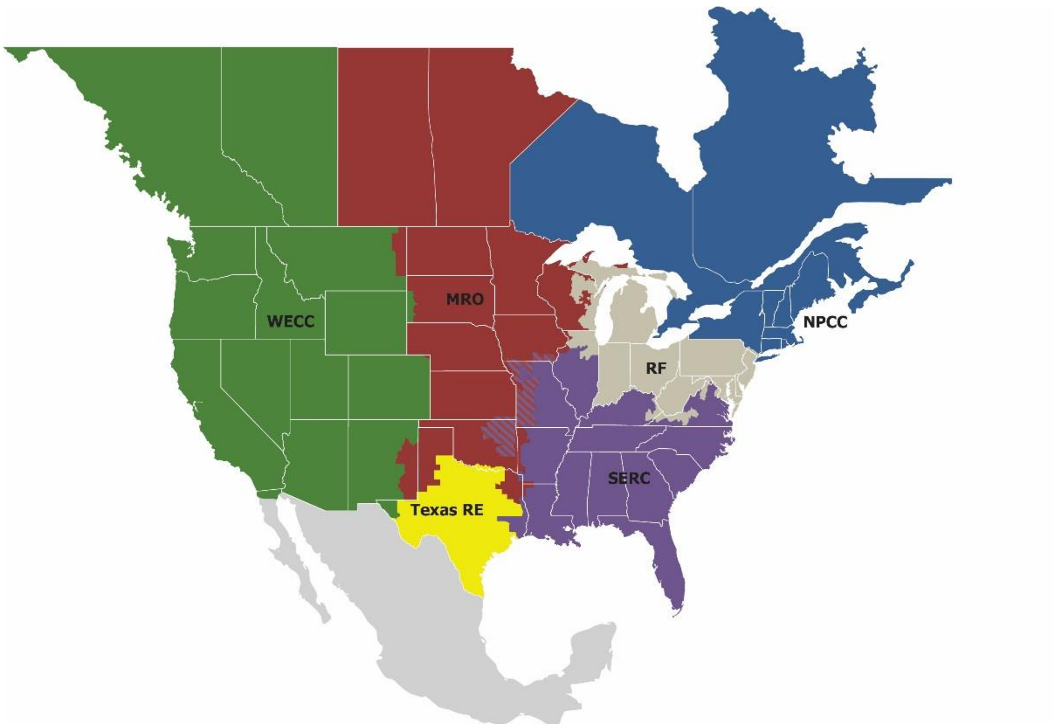
Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of the North American Electric Reliability Corporation (NERC) and the six Regional Entities (REs), is a highly reliable and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

Reliability | Resilience | Security
Because nearly 400 million citizens in North America are counting on us

The North American BPS is divided into six RE boundaries as shown in the map and corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one Region while associated Transmission Owners/Operators participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Introduction

This document entails the detailed portions of analysis done for the DOE CERTS funded project that was coordinated under the NERC Synchronized Measurements Subcommittee industry group. This chapter's content is identified by an appendix lettering system to coordinate enumeration between this *Detailed Event Analysis* report and the *Interconnections Oscillation Analysis* report. The reports were submitted separately to reduce the file size of the analysis and conclusions of the report. This report should be read alongside the *Interconnection Oscillation Analysis* report for full understanding.[1] All analyses were done with no filtering of the signals unless a significant trend was observed; a bandpass filter on the data with corners at 0.1Hz and 10Hz was applied to the data before analysis. No down sampling was performed. **Table I.1** depicts which data source and algorithm was utilized for reporting the mode shape, damping ratio, and other oscillation parameters. Other algorithms of HTLS, ERA, Matrix Pencil, and Prony were used to confirm the results from the chosen algorithm.

Table I.1: Analysis Reporting Algorithm and Data Source per Event

Interconnection	Event Number	Chosen Algorithm	Chosen Data Source (All relative)
Eastern	Event 1: 2016-02-01	ERA	Bus Frequencies
	Event 2: 2016-04-15	Matrix Pencil	First Derivative of Voltage Phase Angle
	Event 3: 2016-06-17	FSSI/FFDD	Bus Frequencies
	Event 4: 2016-11-27	FSSI/FFDD	Bus Frequencies
	Event 5: 2017-01-12	HTLS	Bus Voltage Phase Angle
	Event 6: 2017-02-14	Matrix Pencil	Bus Voltage Phase Angle
	Event 7: 2017-03-16	HTLS	Bus Frequencies
Texas	Event 1: 2016-01-27	ERA	Bus Voltage Phase Angle
	Event 2: 2016-04-18	Prony	Bus Voltage Phase Angle
	Event 3: 2016-07-10	HTLS	Bus Voltage Phase Angle
	Event 4: 2016-10-23	HTLS	Bus Voltage Phase Angle
	Event 5: 2017-03-10	ERA	Bus Voltage Phase Angle
Western	Event 1: 2016-01-21	HTLS	Bus Frequencies
	Event 2: 2016-01-27	HTLS	Bus Frequencies
	Event 3: 2016-09-08	HTLS	Bus Frequencies
	Event 4: 2016-09-21	Prony	First Derivative of Voltage Phase Angle
	Event 5: 2017-01-20	HTLS	Bus Frequencies
	Event 6: 2017-03-09	HTLS	Bus Frequencies
	Event 7: 2017-05-10	HTLS	Bus Frequencies

It is important to note that the methodology and process between the two reports are consistent and supportive of the other report.

[1] See the other report here in order to view the study group's conclusions and methodologies behind these results

Appendix D: Eastern Interconnection Analysis Results

For the analysis done in this section, the references to the “center point” refer to an average of all the angle or frequency signals as is a commonly used approximation for the system center for the phasor measurement unit (PMU) data. This approximation will dampen down signals close to this center for the mode shape phase. For some events below, data providers gave angle data after unwrapping and subtracting an unknown reference; in these cases, frequency data was the only source for analysis.

Event 1: 2016-02-01 15:02:29 UTC

This event involved a resource loss that was estimated to be 970 MW tripping off-line. The system frequency response is shown in **Figure D.1**. The oscillatory behavior immediately following the generation loss event was analyzed as in input to determine interarea modes. No forced oscillations were observed in this event; the small “sizzle” in frequency is normal for continuous fluctuations in generation and load.

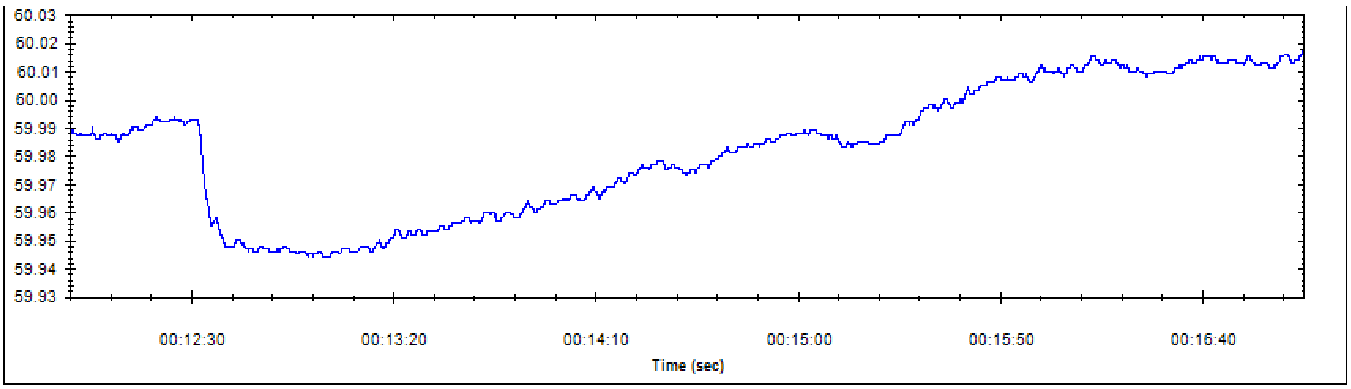


Figure D.1: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes related to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures D.2–Figure D.4.**

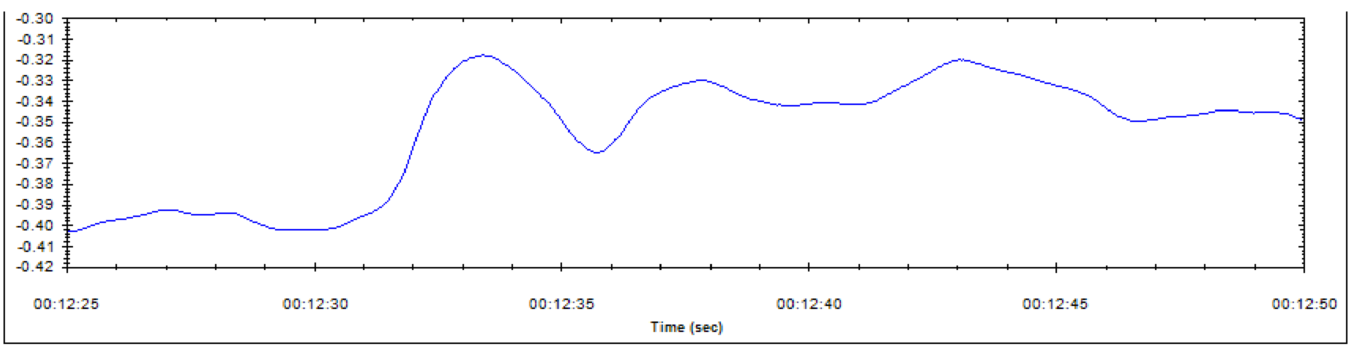


Figure D.2: New England Area Phase Angle with Respect to Center Point

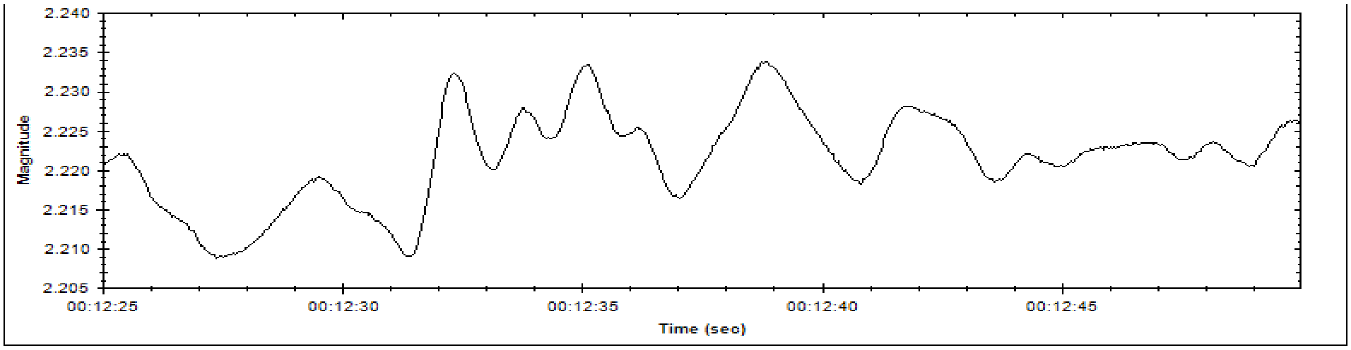


Figure D.3: MISO Area Phase Angle with Respect to Center Point

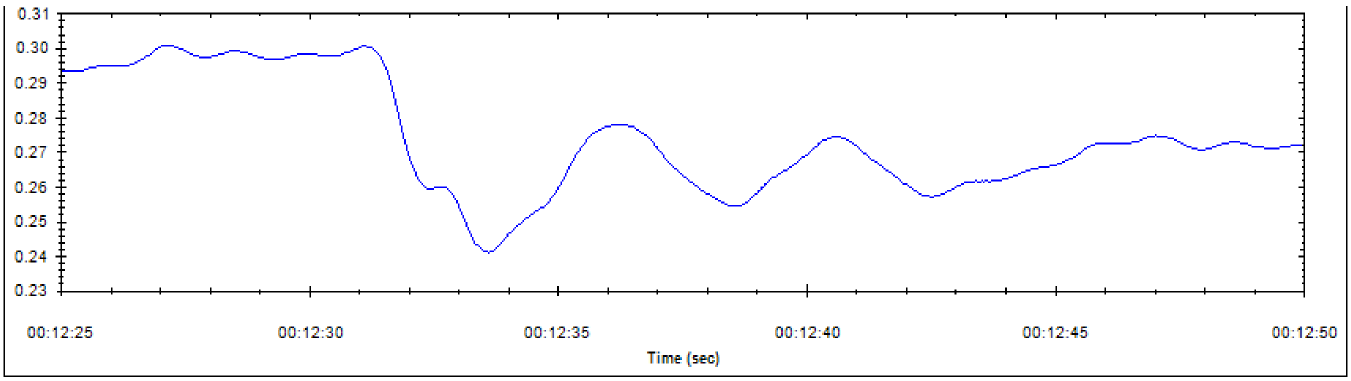


Figure D.4: SOCO Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus frequency signals provided by the Reliability Coordinators (RCs) to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:10:26 to 00:10:34 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:10:23. The analysis window is demonstrated in **Figure D.5.**

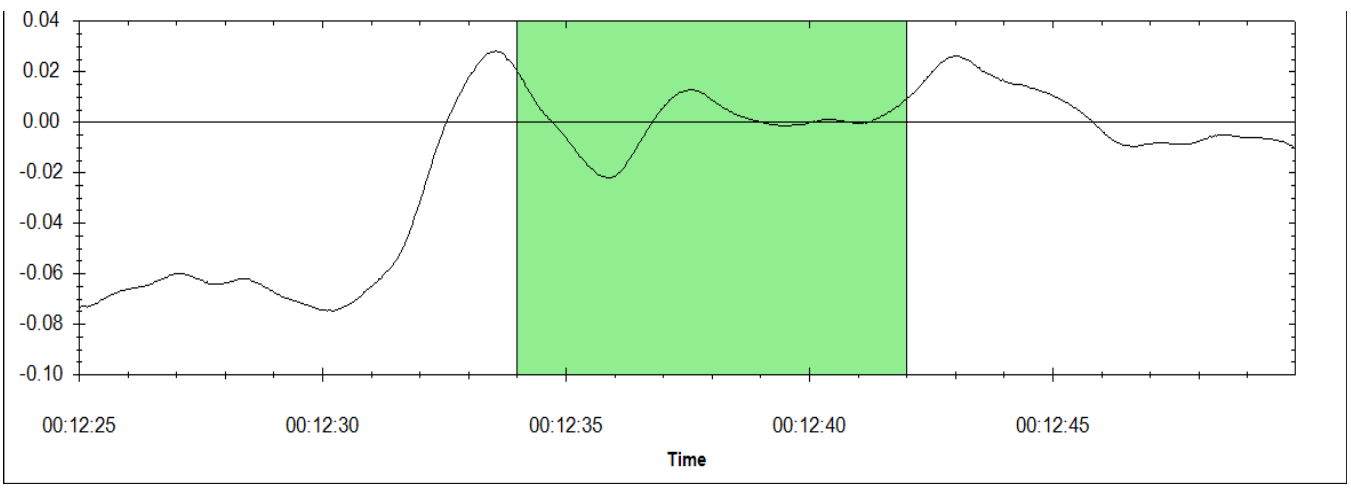


Figure D.5: Ringdown Analysis Window from 00:10:26 to 00:10:34

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match. **Figures D.6–D.8** demonstrate the signal match between the original and reconstructed signals.

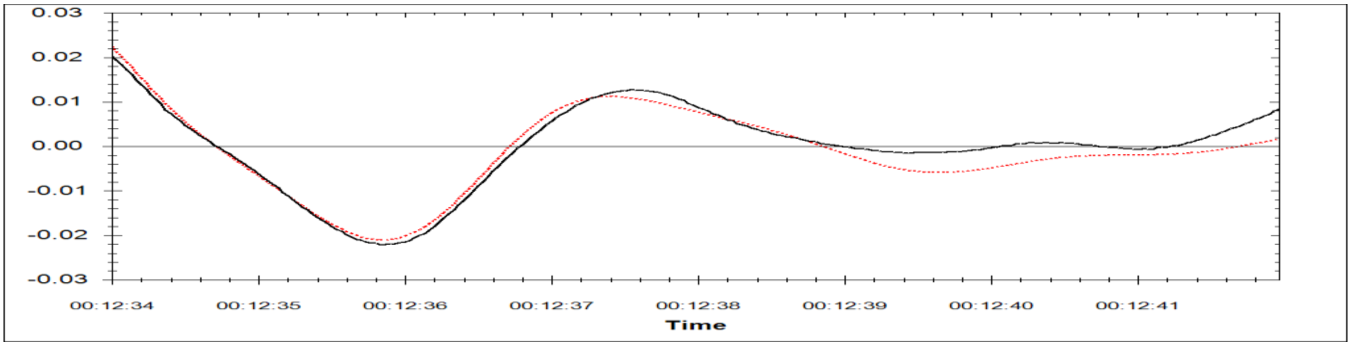


Figure D.6: New England Reconstructed and Original Signals

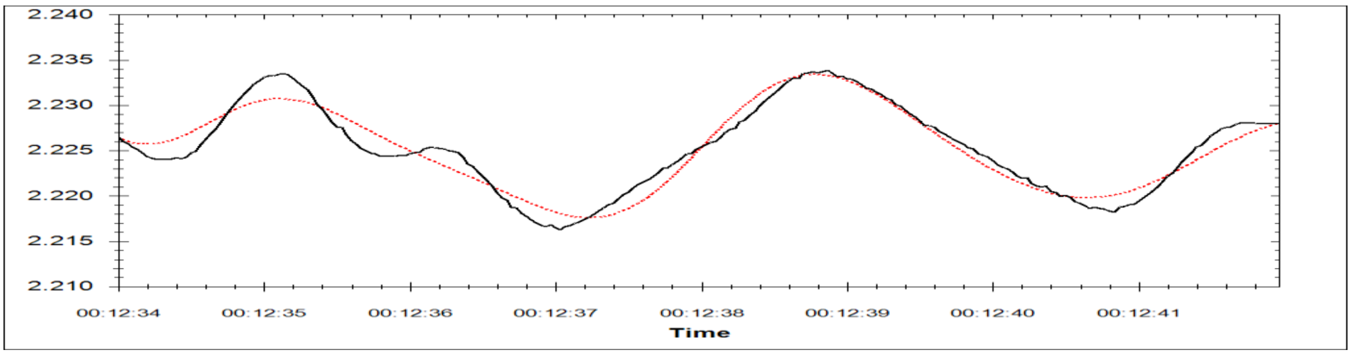


Figure D.7: MISO Reconstructed and Original Signals

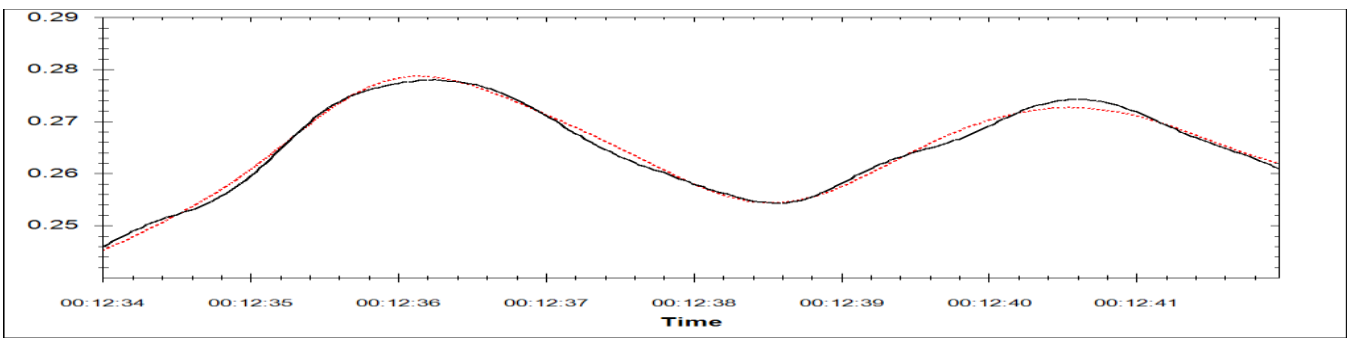


Figure D.8: SOCO Reconstructed and Original Signals

In addition, the spectrum of the lower frequency portions of the signals was analyzed to determine if any mode shape was missed. Figure D.9 demonstrates the best and worst matches in the analysis, indicating that the mode shapes are an accurate depiction of the oscillation.

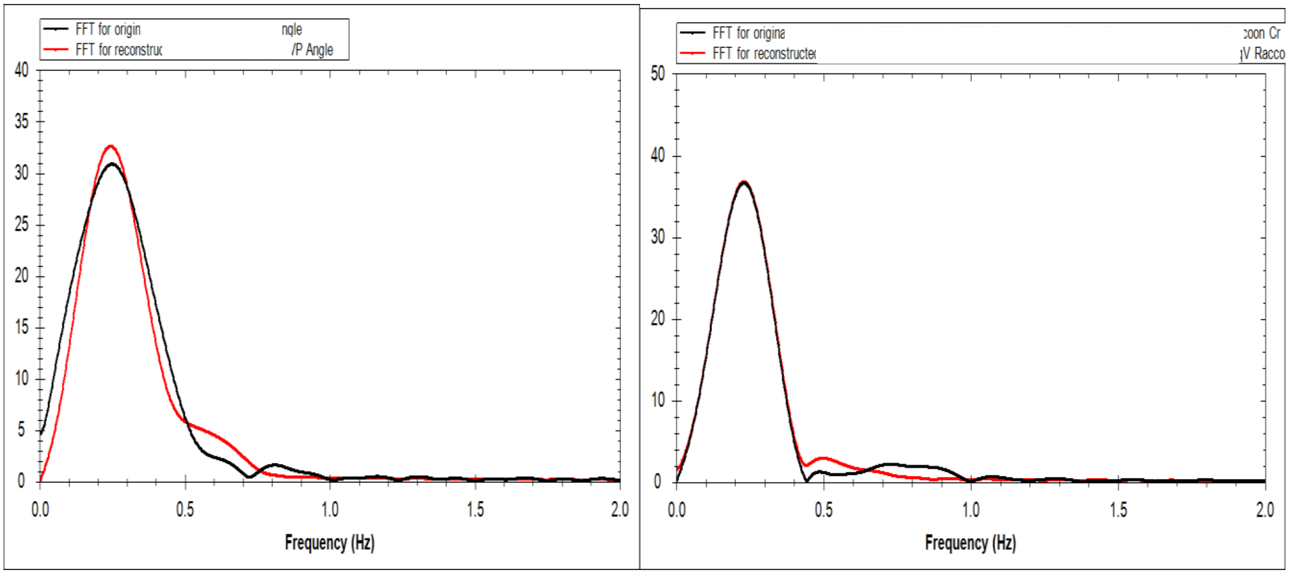


Figure D.9: Reconstructed and Original FFT Results. Left—New England, Right—VACAR

Table D.1 provides the summary of the ERA results from the analysis. Modes with a relative energy of less than 10% are not shown. A total of 14 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the ERA analysis was 146 mHz. A link to the *Frequency Disturbance Report* can be found at the UTK website.[2]

Table D.1: Dominant Modes		
Frequency (Hz)	**Damping (%)**	**Total Energy (%)**
0.23	13.4	93

The mode shapes for the listed mode in Table D.1 can be found in Figure D.10. The 0.23 Hz mode demonstrates a north to south mode as well as some interactions from the west to the east. With the small amount of signals used for this analysis, it makes it hard to fully understand the 0.23 Hz mode shape, and other events with more signals will provide a more accurate depiction for the mode shape.

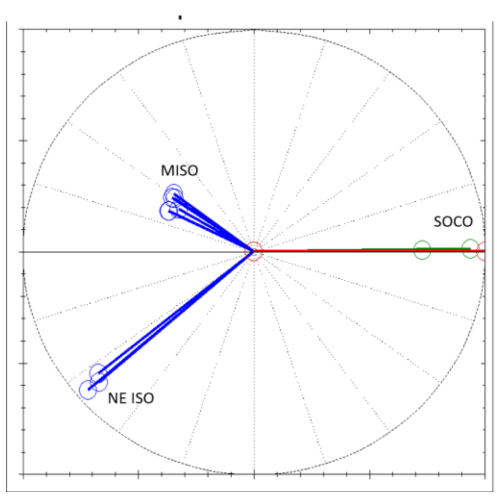


Figure D.10: Mode Shape for 0.23 Hz Mode

[2] Frequency Disturbance Report

Event 2: 2016-04-15 00:05:23 UTC

This event involved a resource loss estimated at 1,200 MW tripping off-line. The system frequency response is shown in **Figure D.11**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

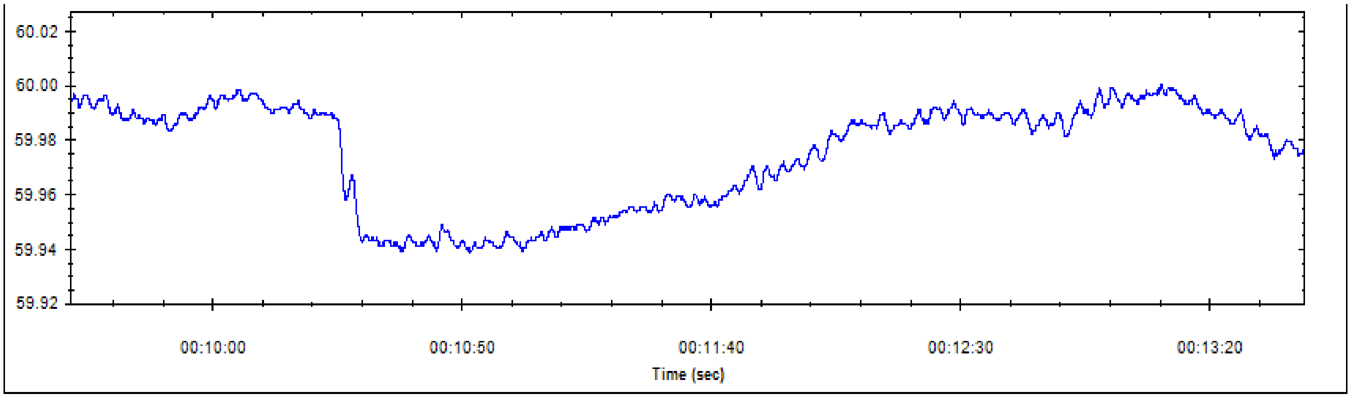


Figure D.11: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures D.12–D.14.**

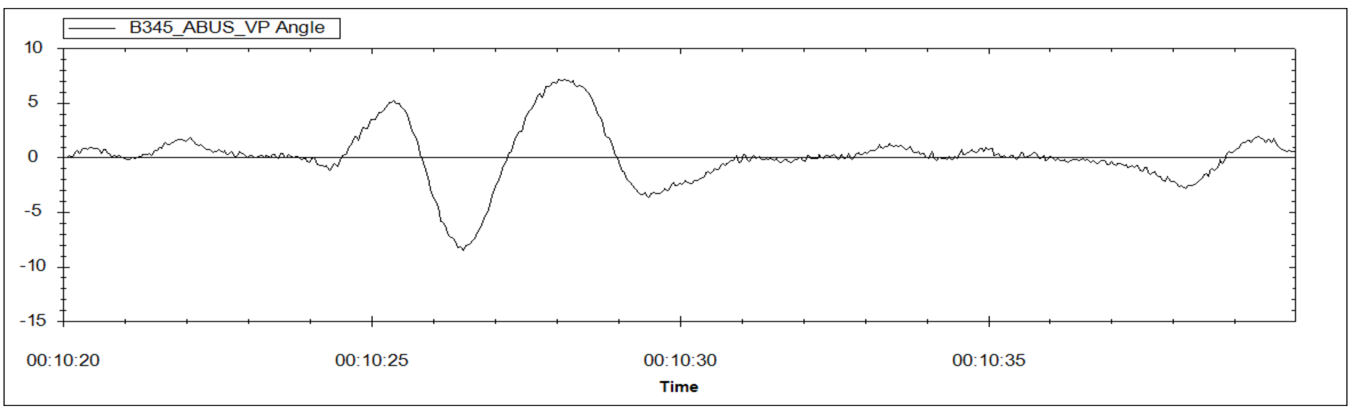


Figure D.12: New England Area Phase Angle with Respect to Center Point

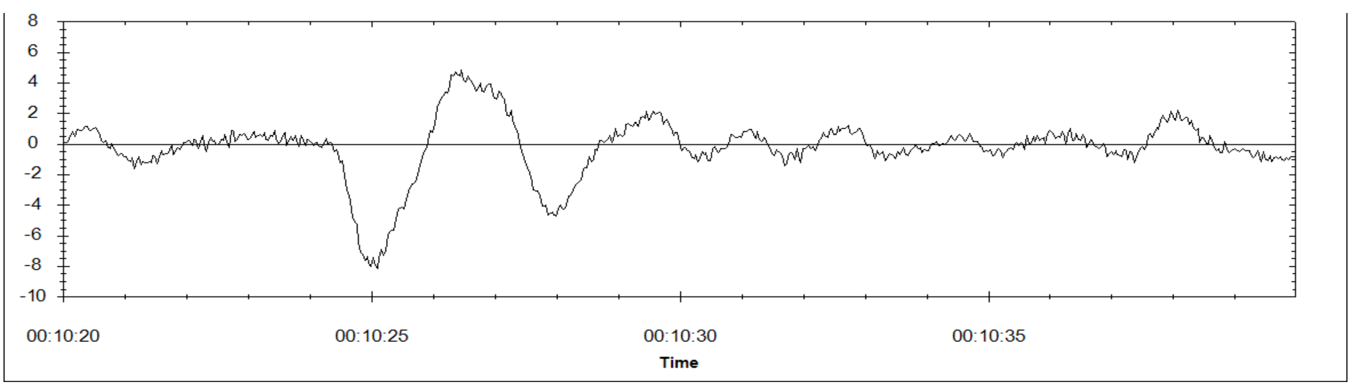


Figure D.13: VACAR Area Phase Angle with Respect to Center Point

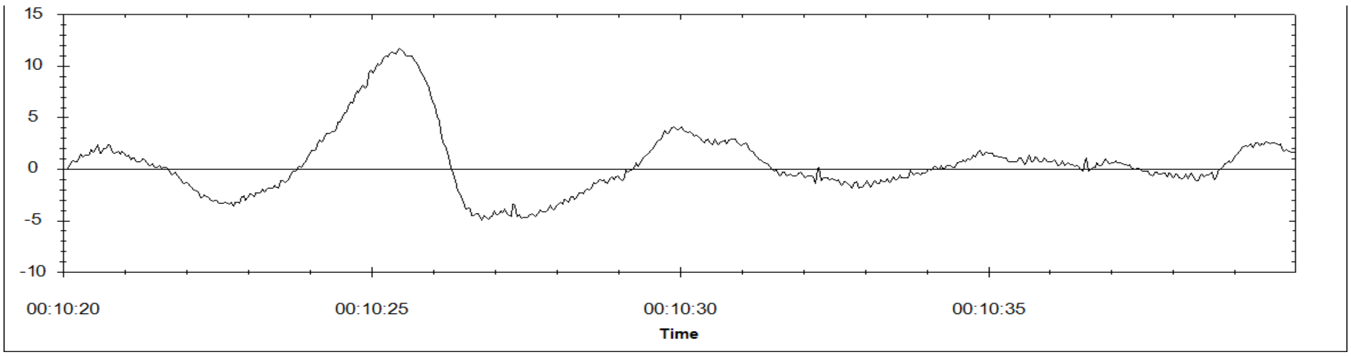


Figure D.14: Florida Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized voltage phase angle derivative signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:10:26 to 00:10:34 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:10:23. The analysis window is demonstrated in **Figure D.15.**

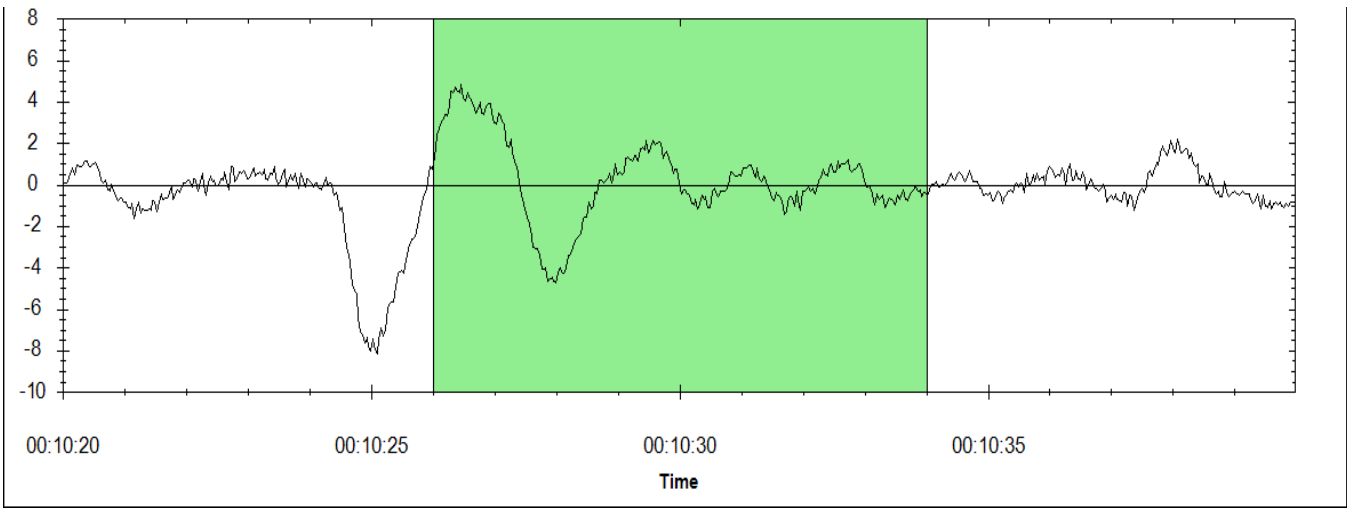


Figure D.15: Ringdown Analysis Window from 00:10:26 to 00:10:34

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures D.16–D.18** demonstrate the signal match between the original and reconstructed signals.

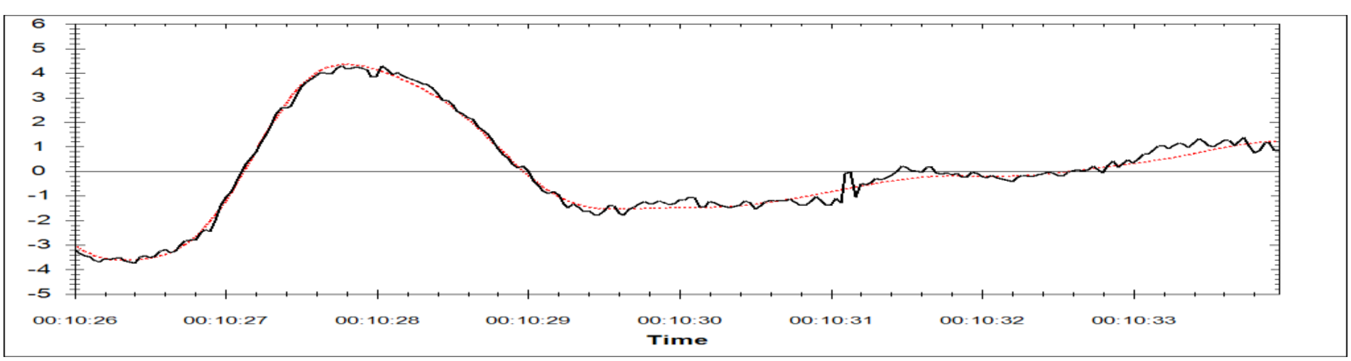


Figure D.16: New England Reconstructed and Original Signals

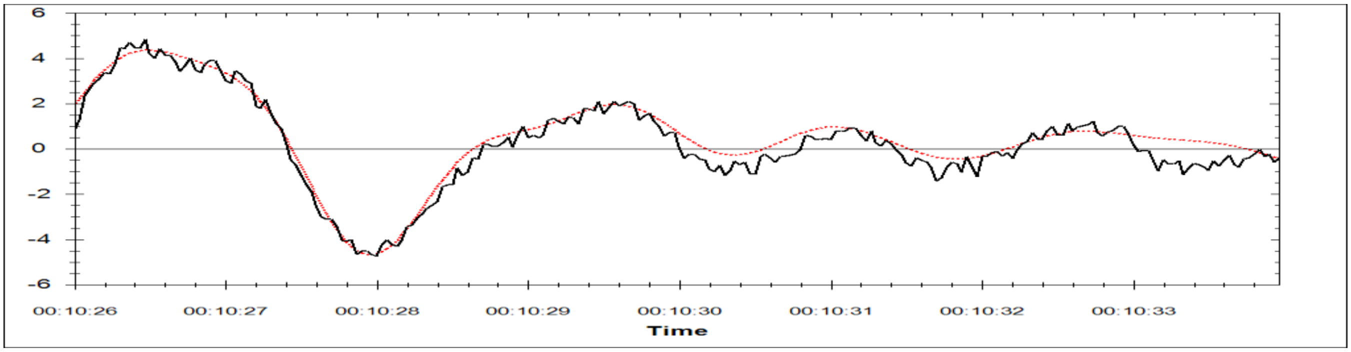


Figure D.17: VACAR Reconstructed and Original Signals

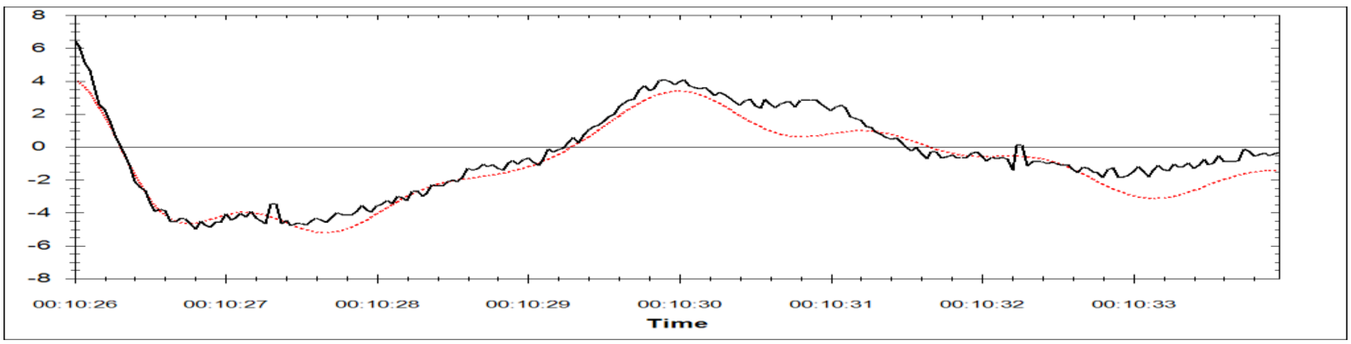


Figure D.18: Florida Reconstructed and Original Signals

In addition, the spectrum of the lower frequency portions of the signals was analyzed to determine if any mode shape was missed in analysis. Figure D.19 demonstrates the best and worst matches in the analysis, indicating that the mode shapes are an accurate depiction of the oscillation.

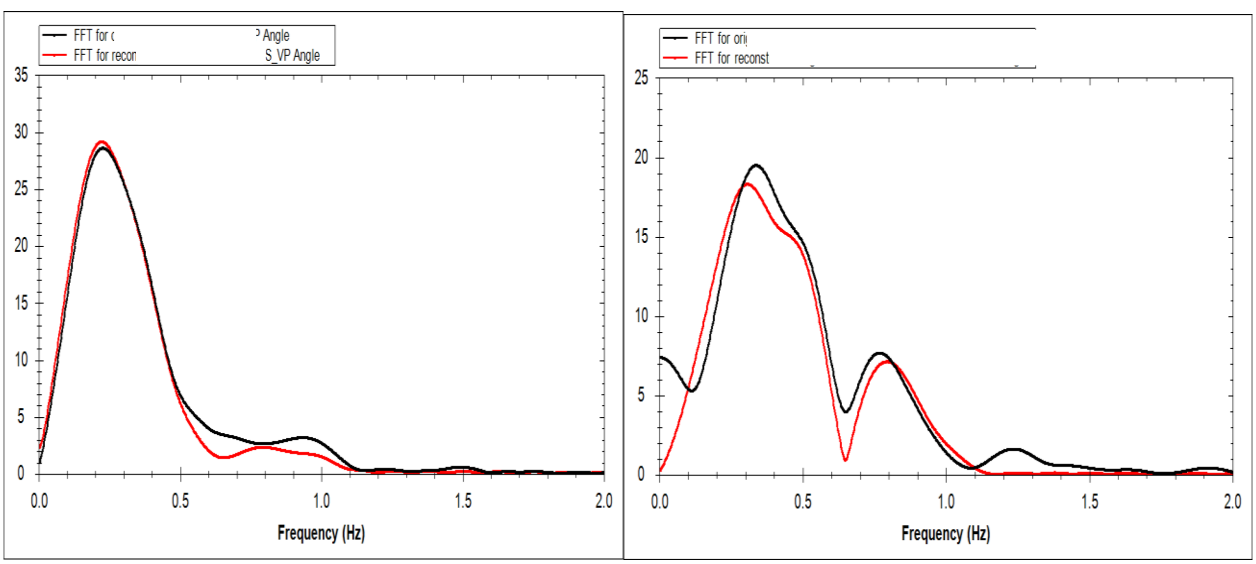


Figure D.19: Reconstructed and Original FFT results. Left—New England, Right—VACAR

Table D.2 provides the summary of the matrix pencil engine results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 70 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the Matrix Pencil analysis was 146 mHz. A link to the *Frequency Disturbance Report* can be found at the UTK website.[3]

Table D.2: Dominant Modes		
Frequency (Hz)	**Damping (%)**	**Total Energy (%)**
0.32	20	79
0.17	13	16

The mode shapes for the listed modes in **Table D.2** can be found in **Figures D.20** and **D.21**. The 0.17 Hz mode demonstrates a north to south mode and the 0.32 Hz mode demonstrates a complex mode shape that is similar to the June 2016 forced oscillation event (Event 3). Based on the **Figure D.20**, it is apparent that the Northeast regions out of phase with the Florida/VACAR and MISO regions. Since this event was closer to VACAR region, that portion of the mode shape may be more pronounced.

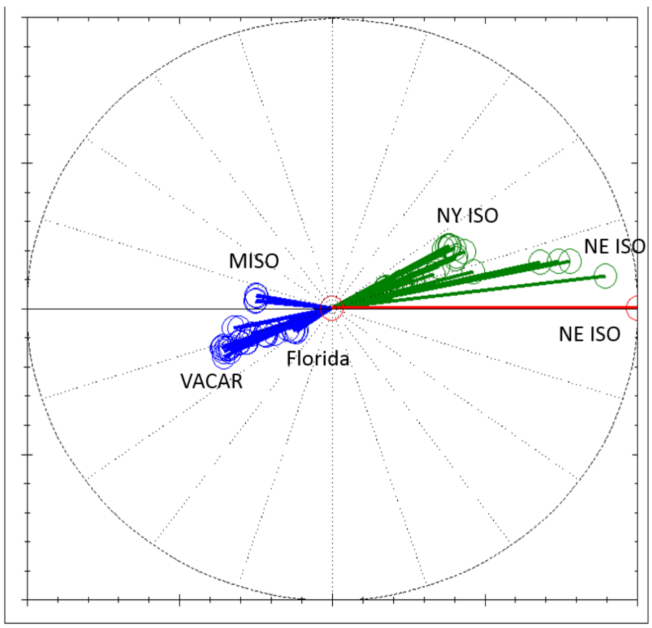


Figure D.20: Mode Shape for 0.32 Hz Mode

3 Frequency Disturbance Report

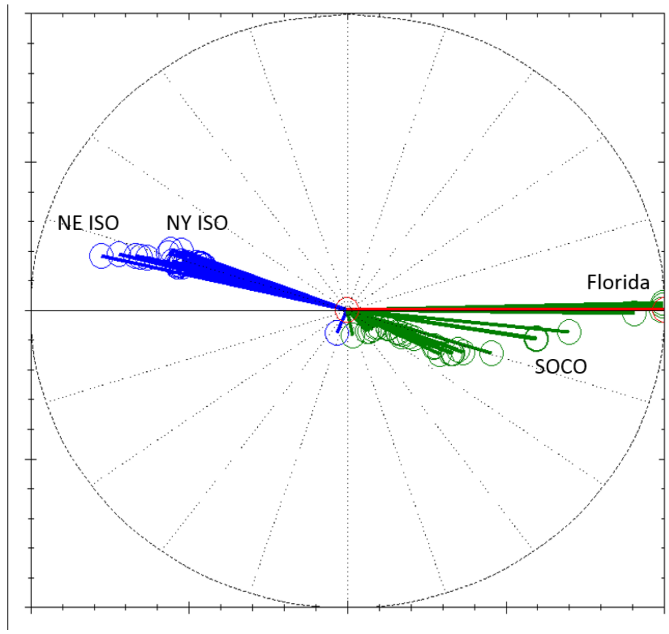


Figure D.21: Mode Shape for the 0.17 Hz Mode

Event 3: 016-06-17 07:00:00 UTC

In Event 3, a forced oscillation event caused a natural system mode to be excited due to a small resonance effect. Prior to the starting of the oscillatory event, a secondary, much higher frequency forced oscillation was present. This secondary forced oscillation had minimal impact on the natural system modes. Interestingly enough, the harmonics of this forced oscillation were around the same frequency of the forced oscillations found in Event 4.

In the case of Event 3, however, the forced oscillation was a 0.28 Hz sourced in the East Southern Central United States. In **Figure D.22**, the frequency proximity of the forced oscillation is demonstrated. The system mode at the time of analysis had a damping ratio of 10%, signifying that the natural mode shape was well damped.

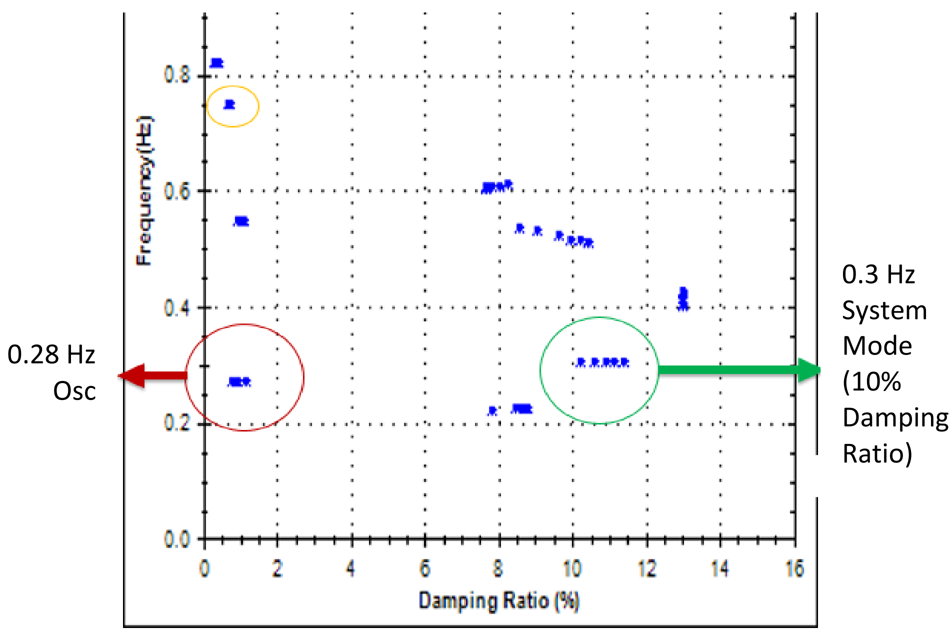


Figure D.22: Frequency vs Damping Ratio during Event 3

The natural system mode shapes can be seen in Figures D.23 and D.24, the red line indicating the relative participation factor of the forced oscillation source. As the participation factor was not large in the 0.3 Hz natural system mode, the overall resonance effect was largely influenced by its frequency proximity rather than its participation factor. This is in direct contrast to the 0.2 Hz natural system mode shape, where the participation factor of the forced oscillation was much higher; however, the frequency difference was also much greater. Thus, for both natural system modes, Event 3 contained mild resonance effects with the natural system modes. The main effect demonstrated in Event 3 was caused by the 0.3 Hz mode rather than the 0.2 Hz mode based on the mode shape analysis. The South Atlantic Census Region was in phase with the West North Central Census Region, which is indicative of the 0.3 Hz natural system mode rather than the 0.2 Hz natural system mode. The 0.3 Hz natural system mode demonstrates a Northwest to Southwest to Southeast geographic relationship.

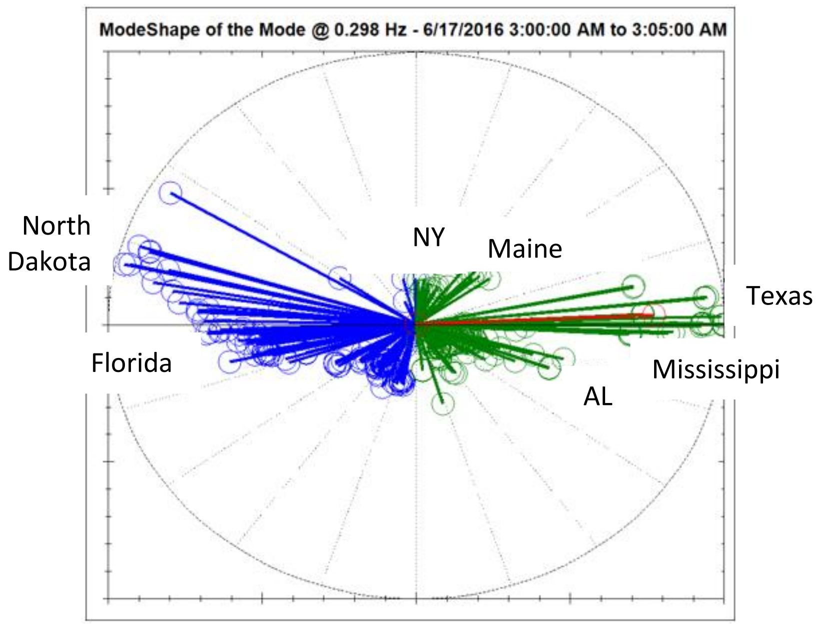


Figure D.23: 0.3 Hz Natural System Mode

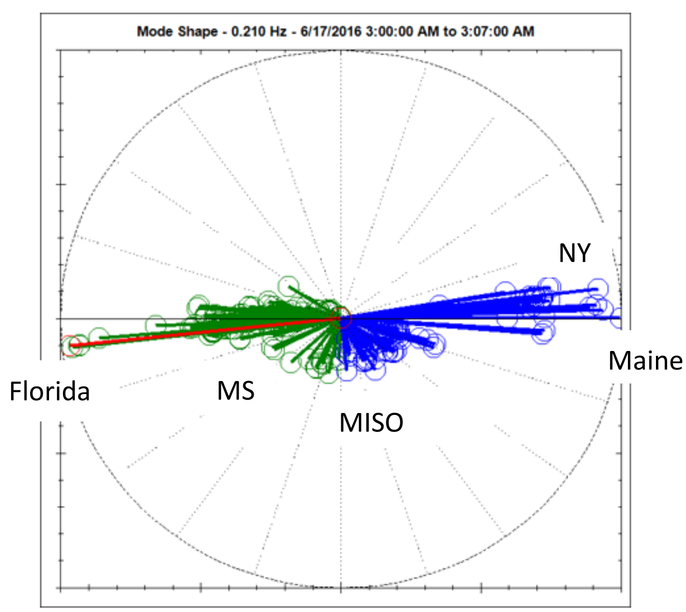


Figure D.24: 0.2 Hz Natural System Mode

Four different regions received oscillatory alarms, (in the North East Census Region, down to East South Central Census Region, and Midwestern Census Regions) while only one region should take action. This event clearly demonstrates the need for coordination within an entire Interconnection when dealing with forced oscillation behavior, especially during these conditions where the natural area mode is well damped in comparison to the forced oscillation, creating confusion as to the source location and may result in unwarranted actions to mitigate the oscillations. The source of the forced oscillation was identified as a control error from a large generation facility, whose location can be seen as the large participation factor in **Figure D.25**.

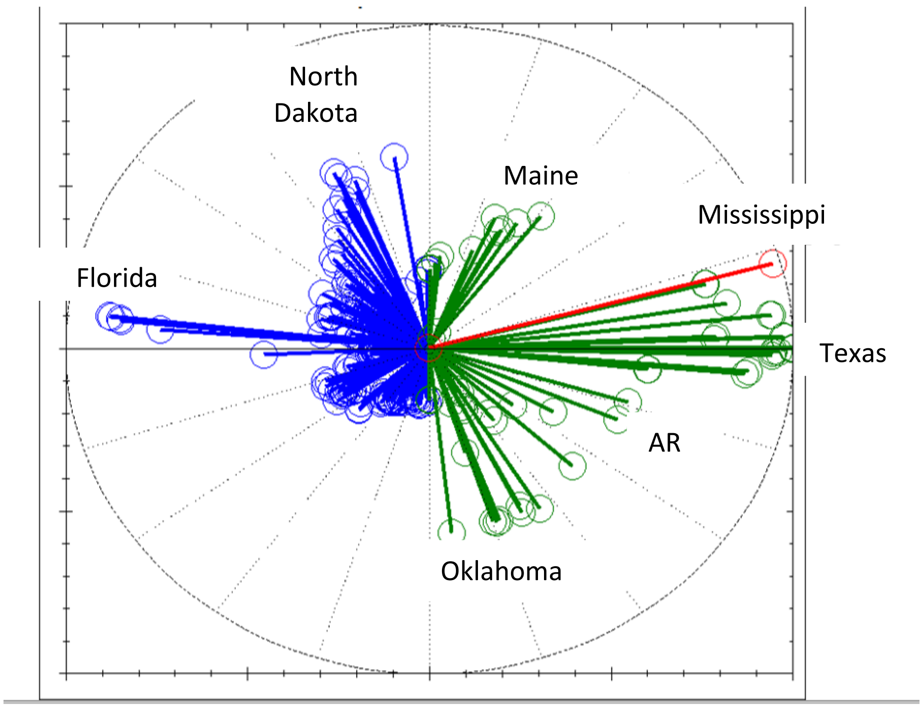


Figure D.25: 0.28Hz Forced Oscillation Mode Shape

Event 4: 2016-11-27 05:40:00 UTC

Event 4 contained another forced oscillation event that had a more complex interaction between the forced oscillation and the excited system modes. Two separate forced oscillation frequencies demonstrated minor resonance between their respective system modes; however, each forced oscillation was close enough to the system frequency that a single forced oscillation frequency could have excited both modes. Thus, each forced oscillation frequency was analyzed to determine its relative impact.

Before the event, a 0.75 Hz forced oscillation was found in the data and it resonated with the 0.78 Hz and 0.67 Hz system modes as demonstrated in **Figure D.26.**

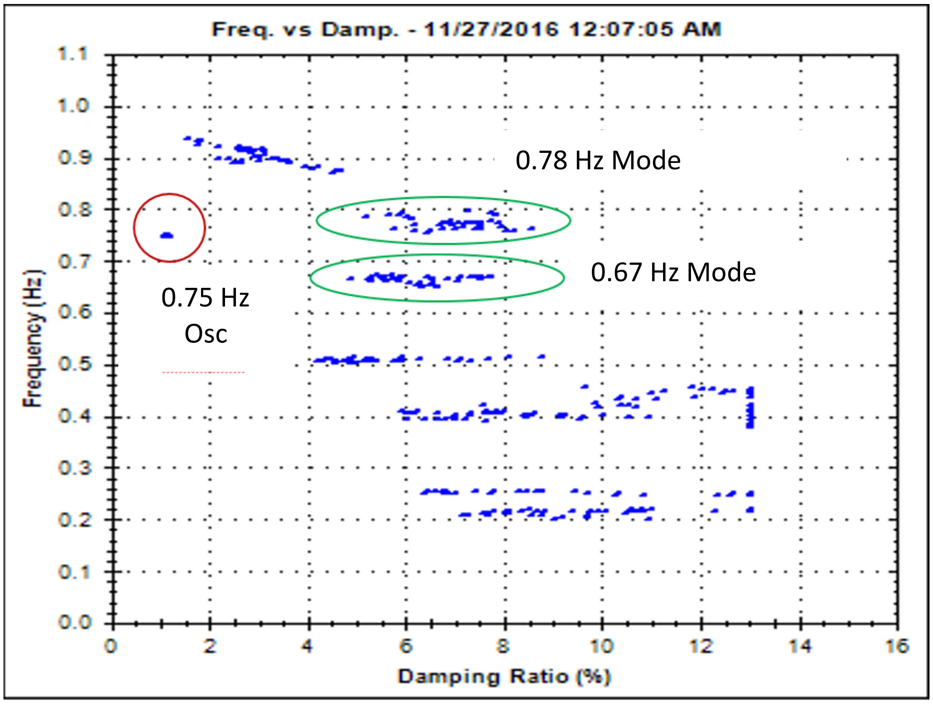


Figure D.26: Frequency vs Damping Ratio Prior to Forced Oscillation Event

As demonstrated in **Figure D.26**, the system modes excited from the previous forced oscillation event contained mode shapes that are captured in **Figures D.27** and **D.28**.

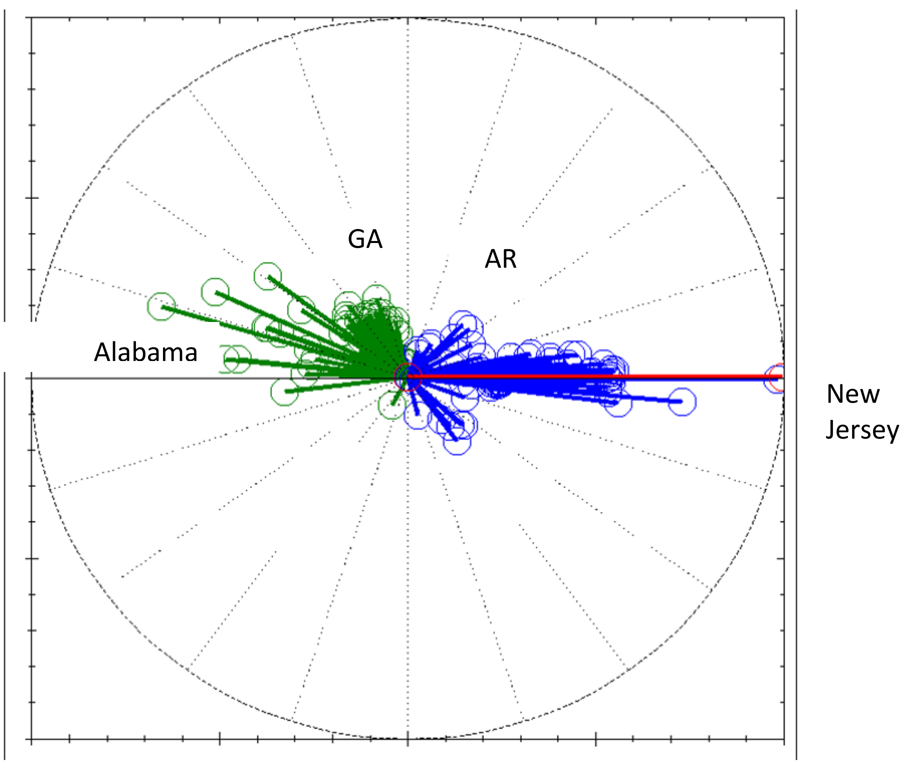


Figure D.27: 0.67 Hz System Mode Shape

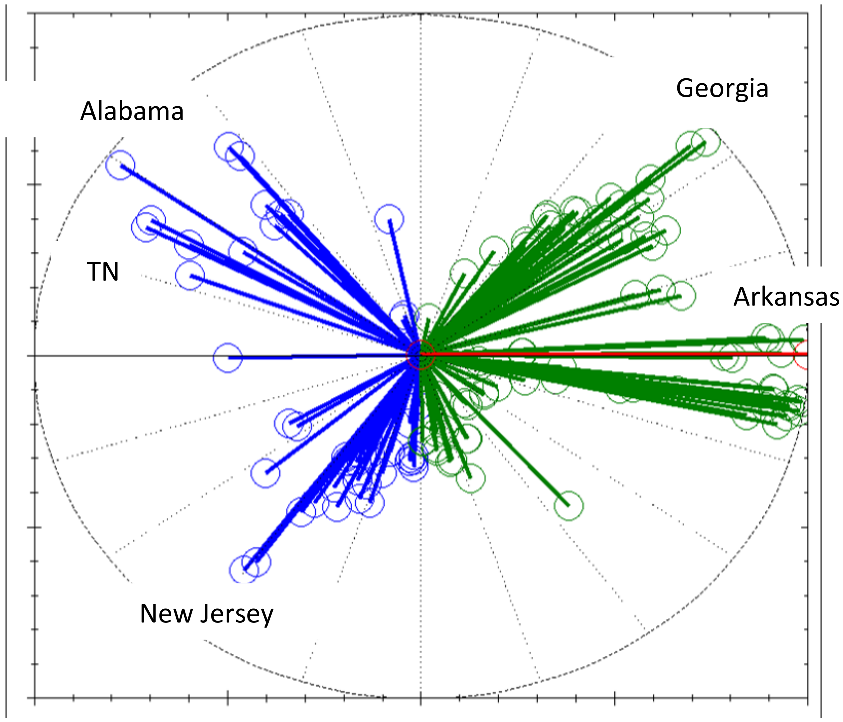


Figure D.28: 0.78 Hz System Mode Shape

During the forced oscillation event; however, the presence of a second forced oscillation during the event altered the mode shape to look slightly different in the participation factors in the mode due to the source of the forced oscillation. Figure D.29 demonstrates the identification of this second forced oscillation and Figures D.30 and D.31 provide the changed system mode shapes. As demonstrated in the figures, the overall shape of the system modes are similar, yet altered slightly due to the resonance effects in the oscillations.

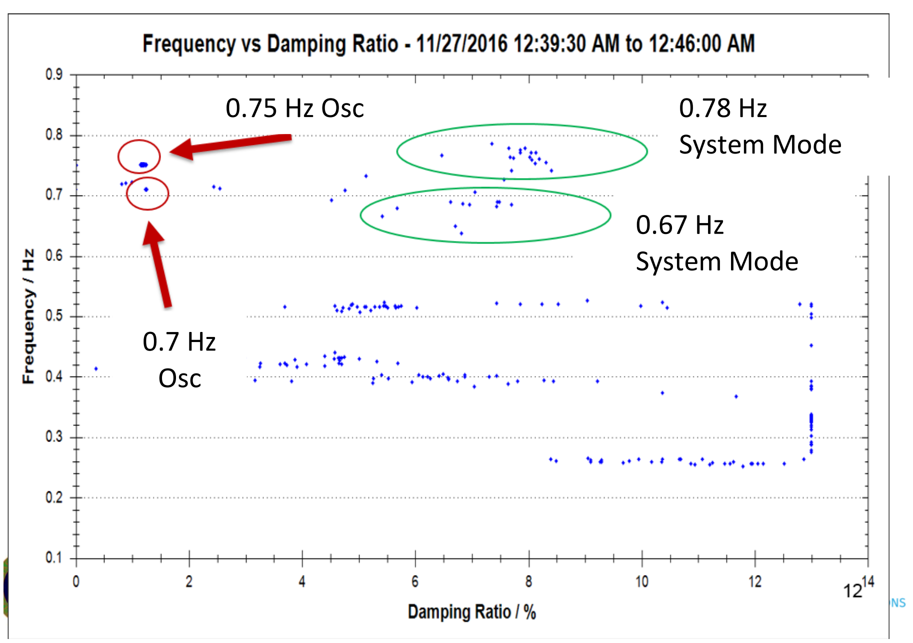


Figure D.29: FSSI Report during the Forced Oscillation Event

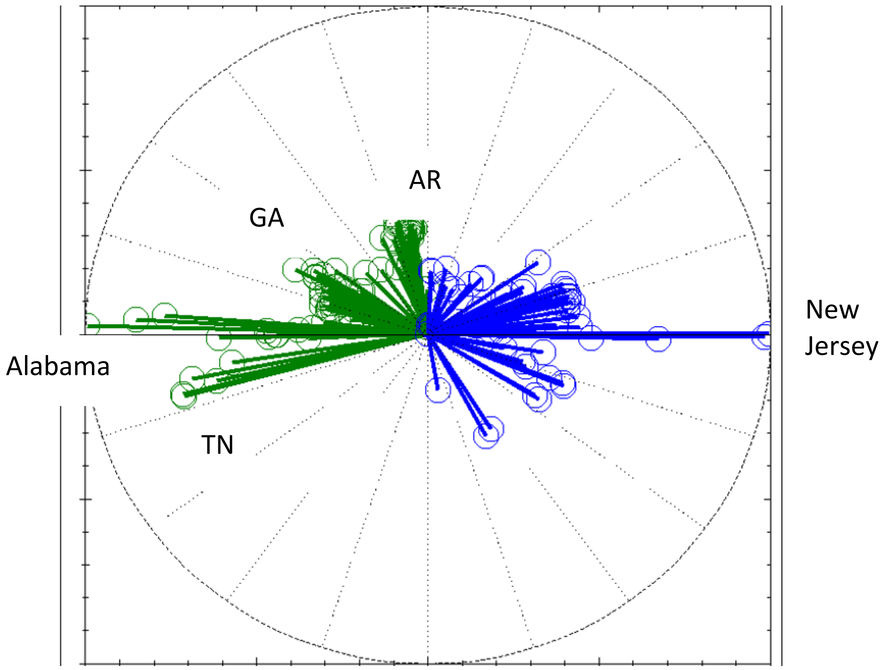


Figure D.30: 0.69 Hz System Mode Shape

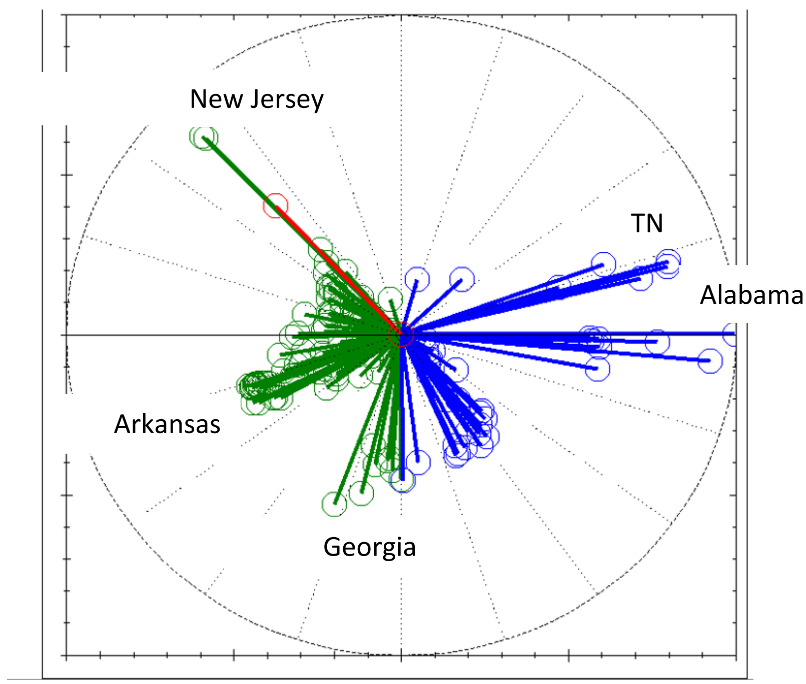


Figure D.31: 0.76 Hz System Mode Shape

As demonstrated in the mode shape plots, the 0.68 Hz system mode shape has strong participation in the Middle Atlantic and East South Central United States Census Regions against the Northeast United States Census Region. The 0.76-0.78 Hz system mode shape is described as oscillating between each of the identified regions; however, the South Atlantic and East South Central regions are not in phase with each other. Instead, the mode shape takes on a more complex form that resembles three different regions oscillating against each other. **Figures D.32** and **D.33** demonstrate the forced oscillation mode shapes, and directly identify the forced oscillation mode shapes and their signal source as defined by the largest participation factor in the shape. Overall, the forced oscillation mode shapes demonstrate small resonance effects due to their close proximity in frequency to the identified natural system modes since the system modes were well damped during this time interval and had low participation in the system mode for their respective source. If the forced oscillation in the South Atlantic region was higher in frequency (0.76 or 0.77 Hz), there would have been a larger resonance effect since the 0.76 Hz mode shape has a larger participation factor of those respective states in comparison to the 0.68 Hz system mode shape, which was closer to the actual 0.7 Hz forced oscillation mode shape. Furthermore, if the 0.75 Hz oscillation was also closer to a strong participation location, stronger resonance would have been seen. While FNET couldn't track the location of the event, its report can be found at the UTK website.[4]

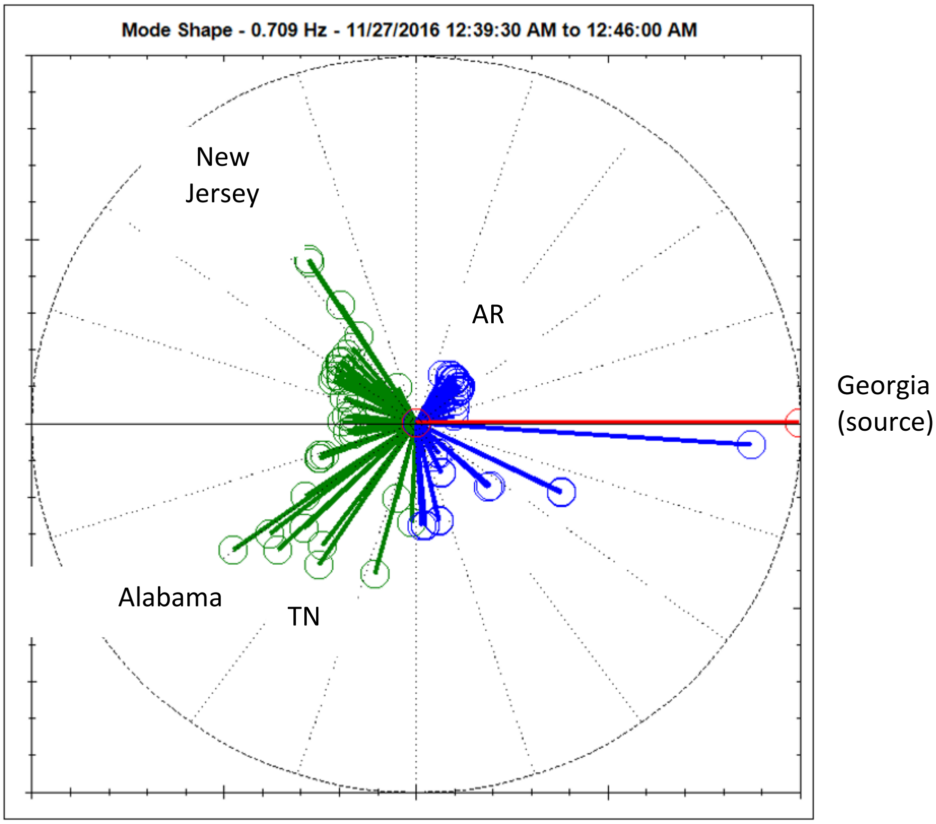


Figure D.32: 0.7 Hz Forced Oscillation

[4] Frequency Disturbance Report

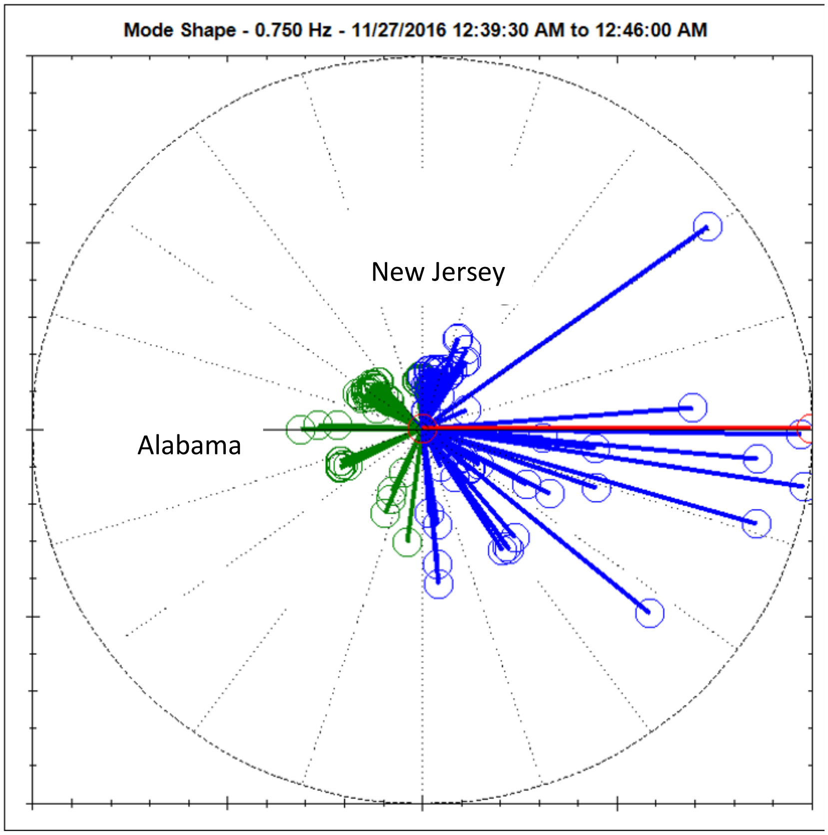


Figure D.33: 0.75 Hz Forced Oscillation

Event 5: 2017-01-12 14:13:22 UTC

This event involved a resource loss estimated at 1300 MW tripping off-line. The system frequency response is shown in **Figure D.34**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

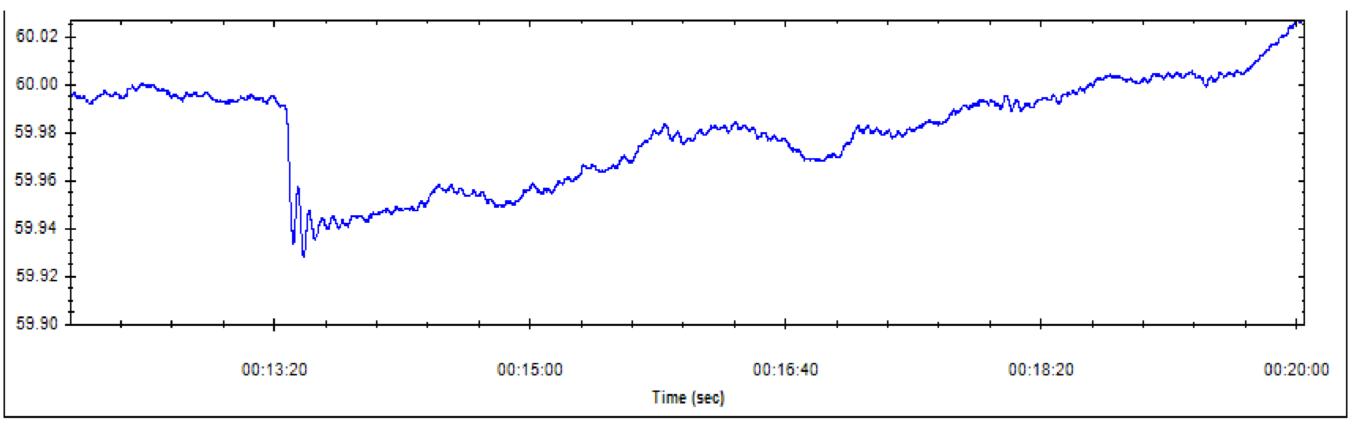


Figure D.34: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures D.35–D.37**.

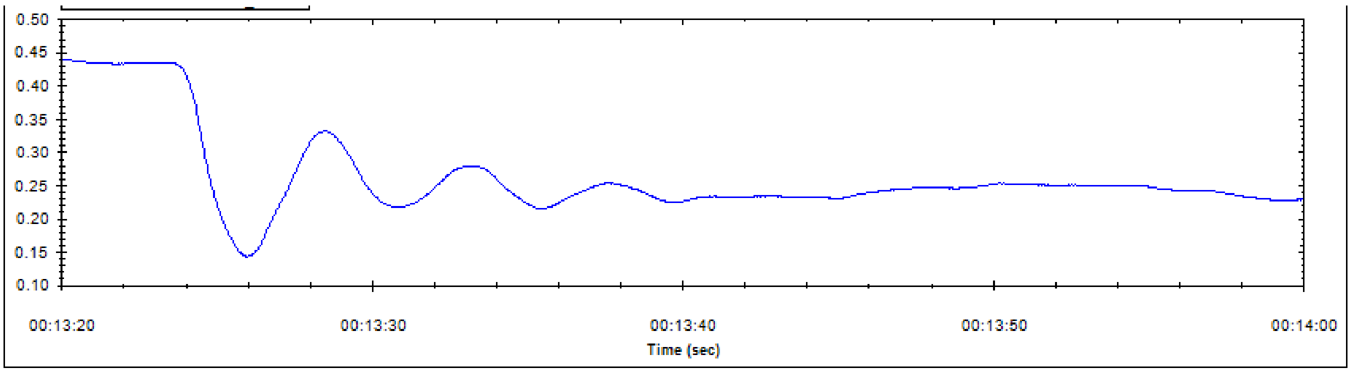


Figure D.35: New England Area Phase Angle with Respect to Center Point

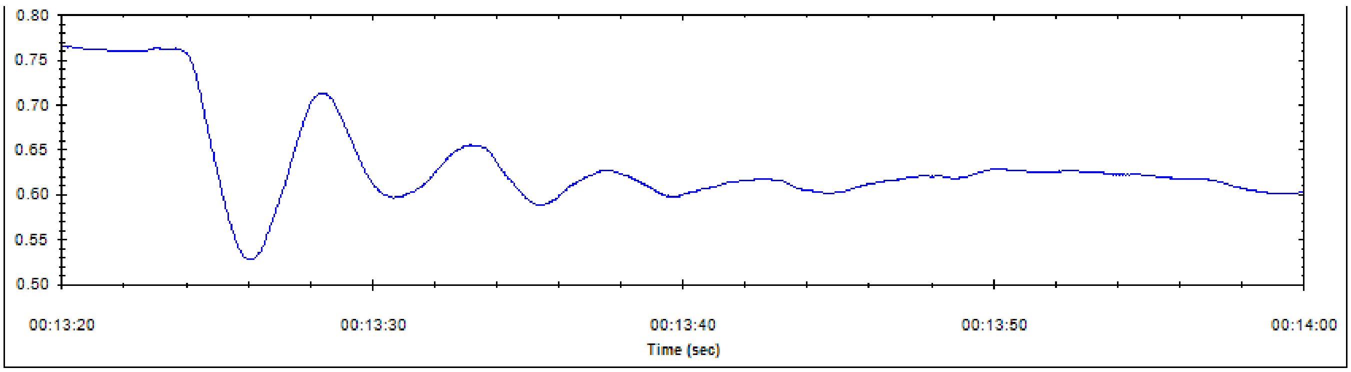


Figure D.36: Ontario Area Phase Angle with Respect to Center Point

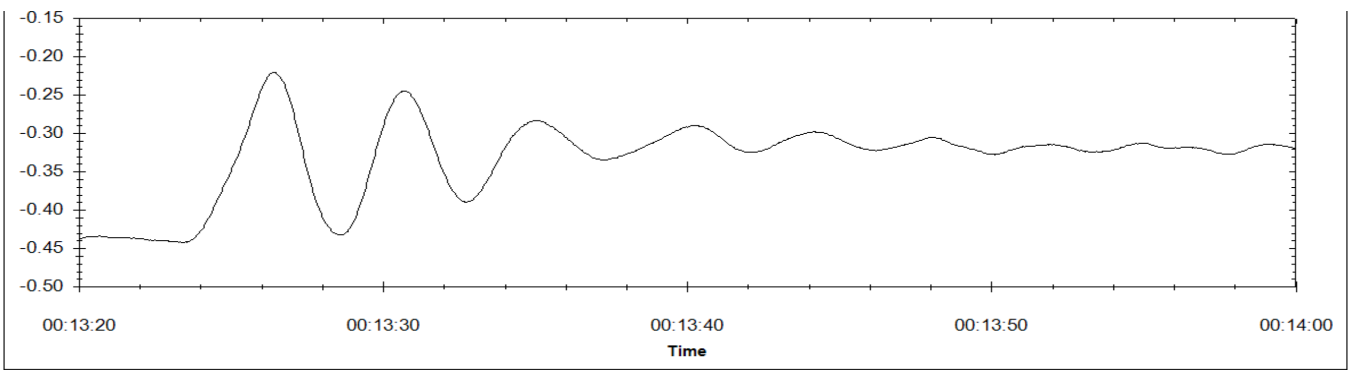


Figure D.37: Florida Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus voltage angle signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:10:26 to 00:10:34 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:10:23. The analysis window is demonstrated in **Figure D.38.**

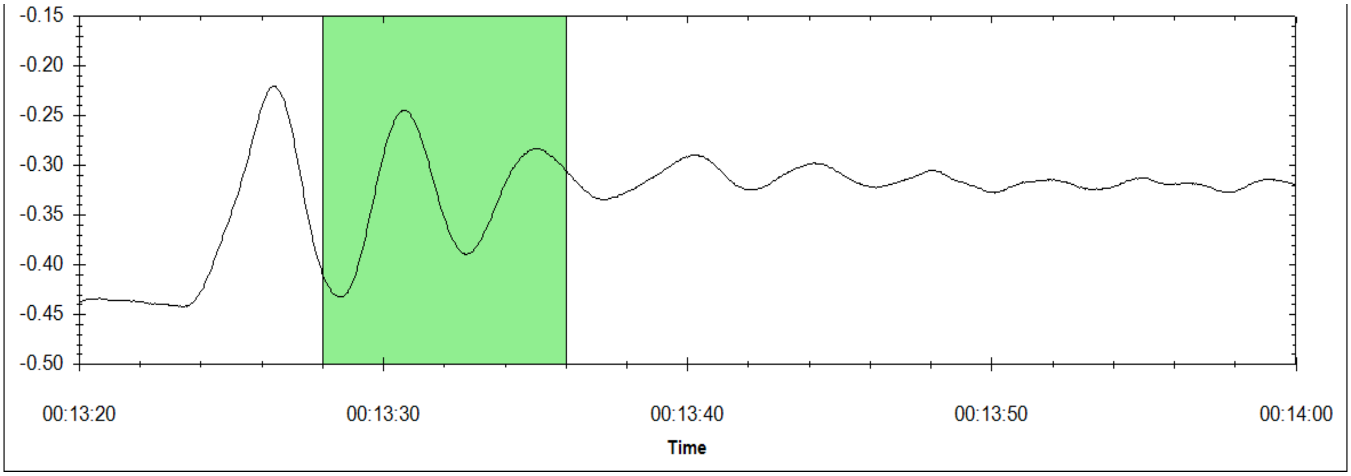


Figure D.38: Ringdown Analysis Window from 00:10:26 to 00:10:34

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures D.39–D.41** demonstrate the signal match between the original and reconstructed signals.

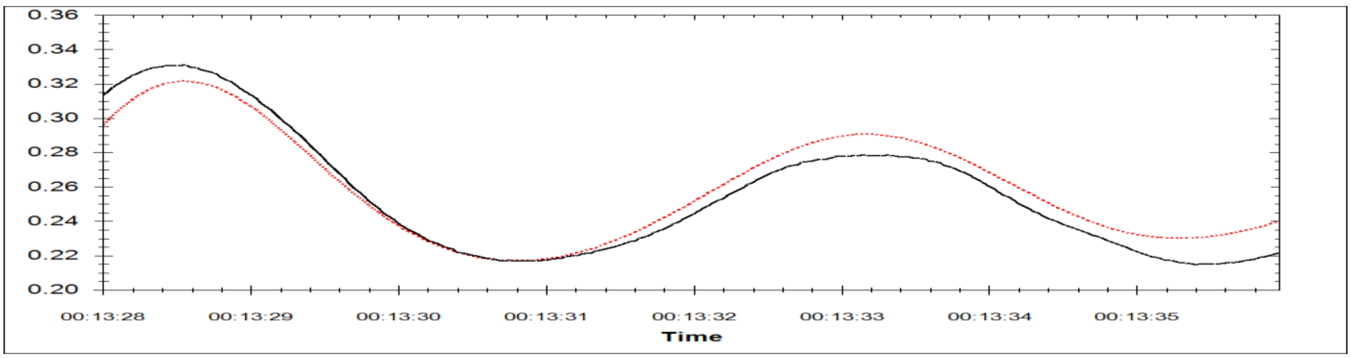


Figure D.39: New England Reconstructed and Original Signals

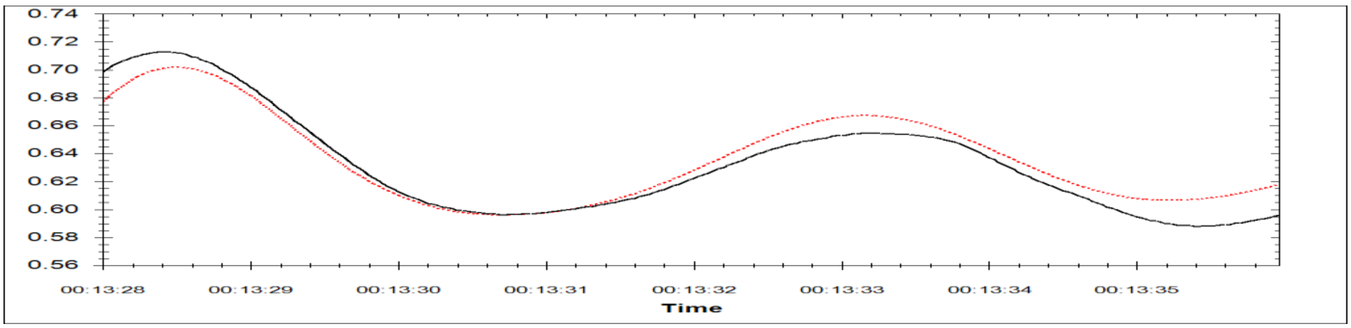


Figure D.40: Ontario Reconstructed and Original Signals

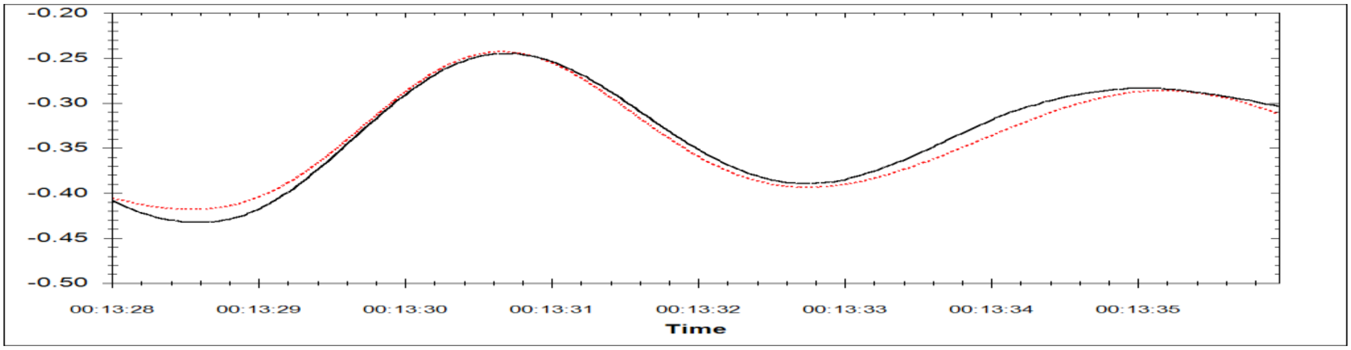


Figure D.41: Florida Reconstructed and Original Signals

In addition, the spectrum of the lower frequency portions of the signals was analyzed to determine if any mode shape was missed in analysis. **Figure D.42** demonstrates the best and worst matches in the analysis and demonstrate that the mode shapes are an accurate depiction of the oscillation.

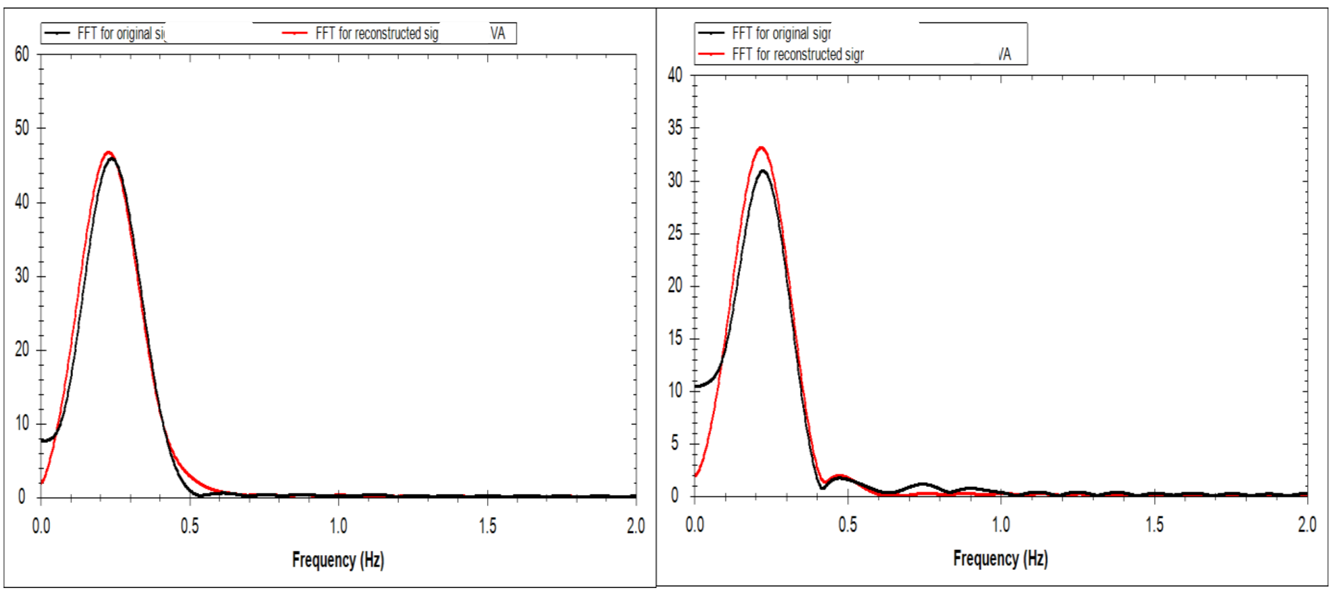


Figure D.42: Reconstructed and Original FFT Results. Left—Florida, Right—New York

Table D.3 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 134 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the HTLS analysis was 451 mHz. A link to the *Frequency Disturbance Report* can be found at the UTK website.[5]

Table D.3: Dominant Modes		
Frequency (Hz)	Damping (%)	Total Energy (%)
0.22	8.3	96

The mode shapes for the listed modes in **Table D.3** can be found in **Figure D.43**. The 0.22 Hz mode exhibited a north to south mode shape similar to that found in the other events. For this mode, we see a strong participation in the Florida and NE ISO regions. This north to south mode shape is very strongly displayed in the mode shape.

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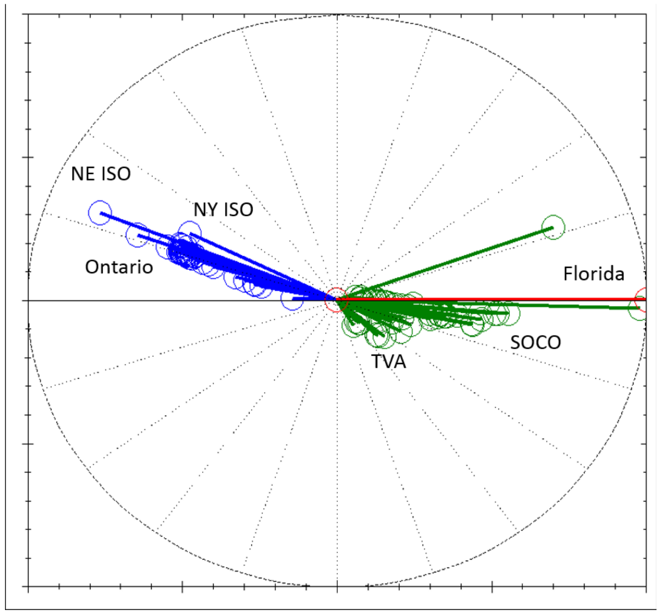

Figure D.43: Mode Shape for 0.22 Hz Mode

Event 6: 2017-02-14 05:09:49 UTC

This event involved a resource loss estimated at 1100 MW tripping off-line. The system frequency response is shown in **Figure D.44**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

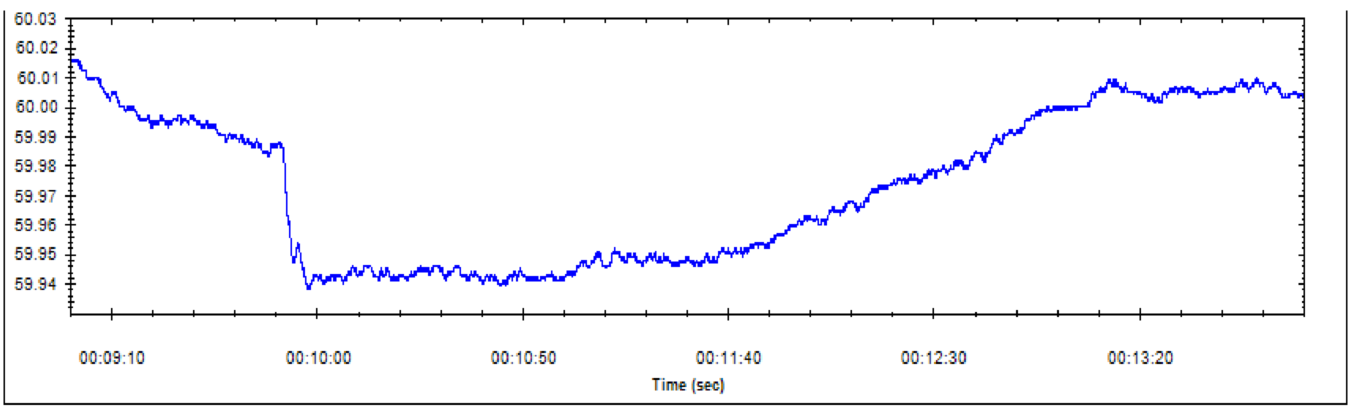

Figure D.44: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures D.45–D.47.**

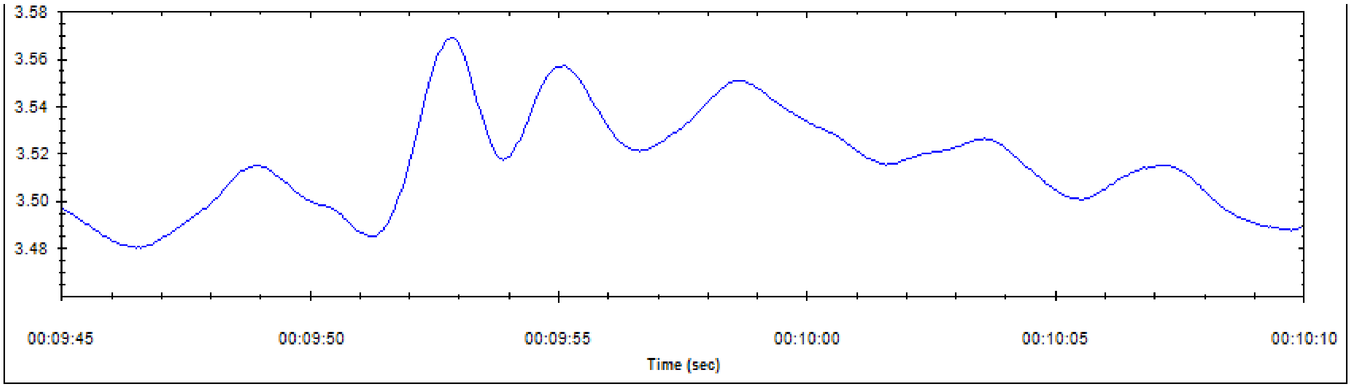

Figure D.45: New England Area Phase Angle with Respect to Center Point

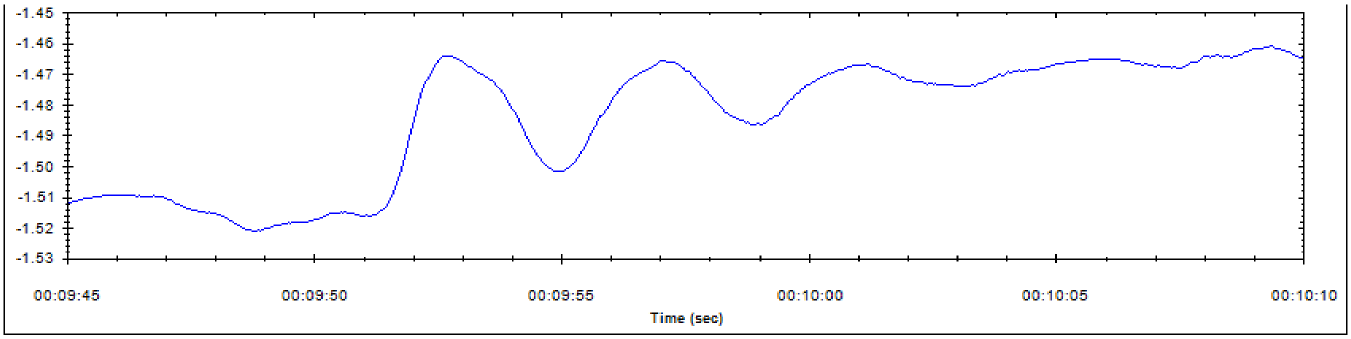

Figure D.46: Georgia Area Phase Angle with Respect to Center Point

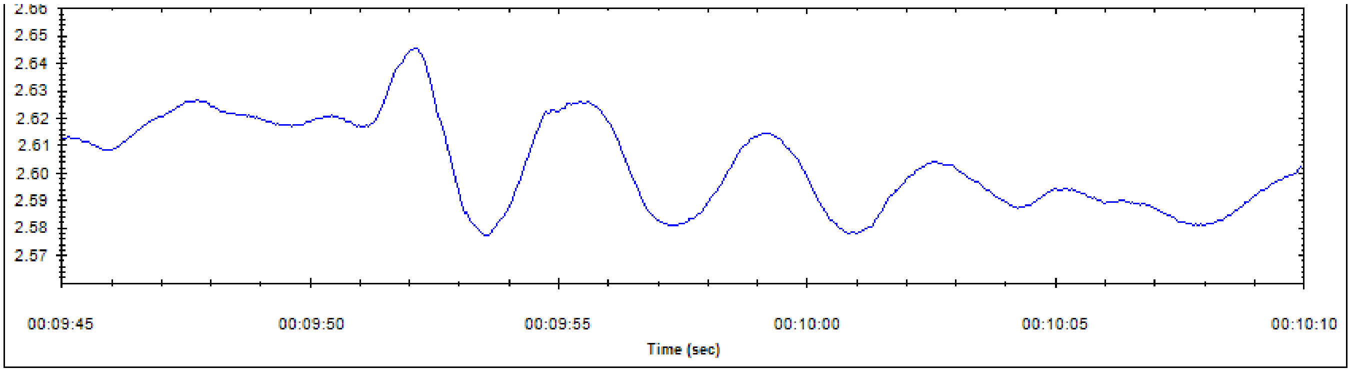

Figure D.47: MISO Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus voltage angle signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:09:56 to 00:10:03 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:09:49. The analysis window is demonstrated in **Figure D.48**.

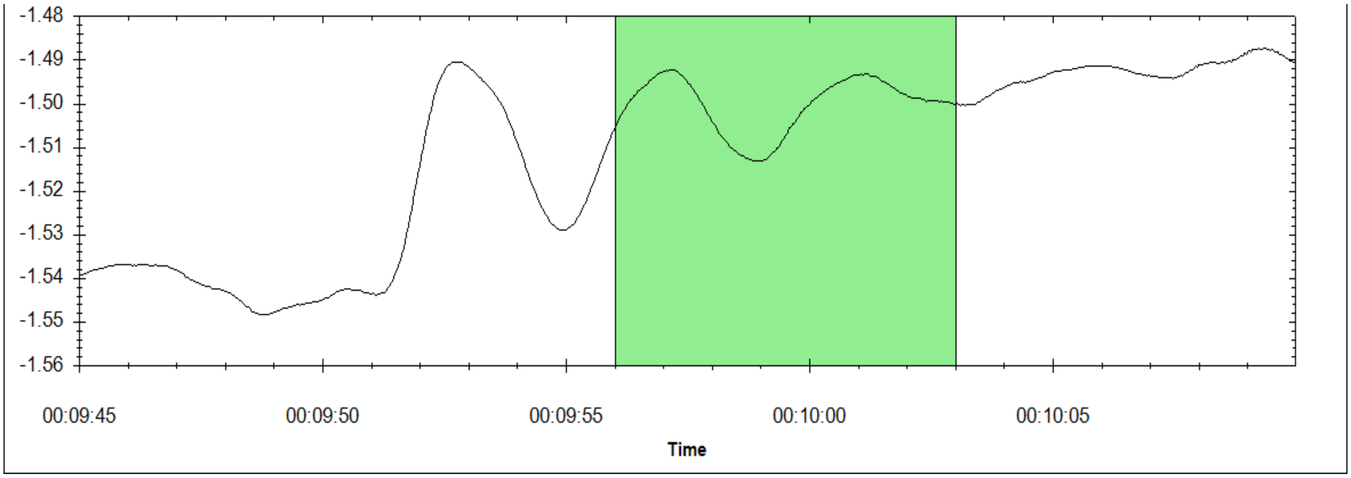

Figure D.48: Ringdown Analysis Window from 00:09:56 to 00:10:03

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. Figures D.49–D.51 demonstrate the signal match between the original and reconstructed signals.

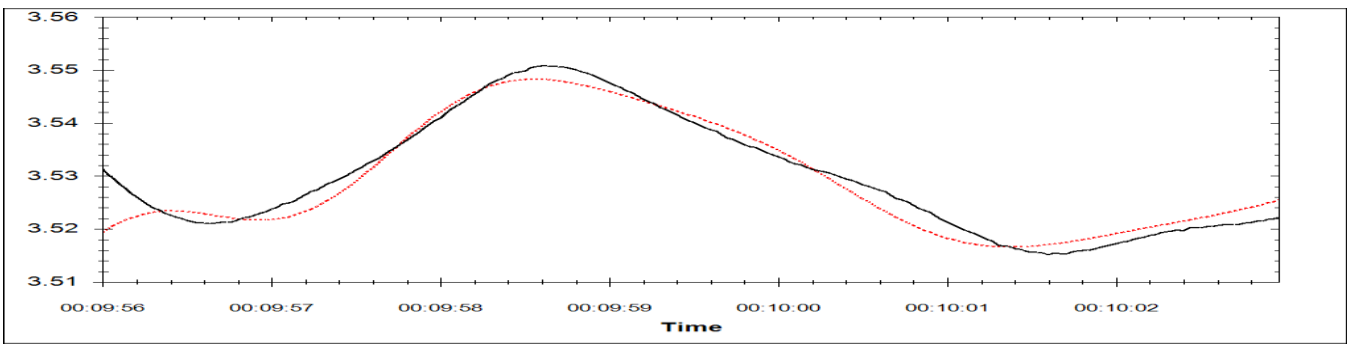

Figure D.49: New England Reconstructed and Original Signals

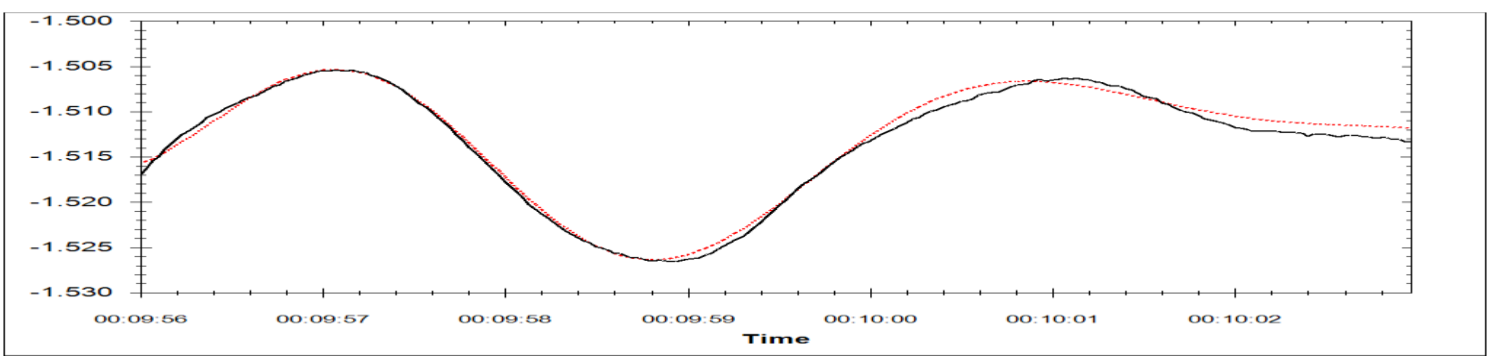

Figure D.50: Georgia Reconstructed and Original Signals

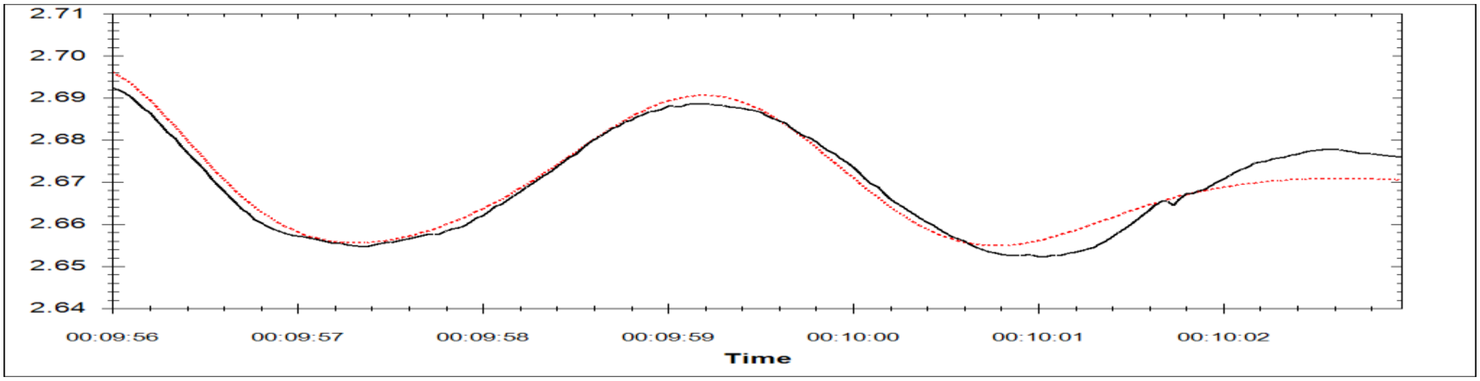

Figure D.51: MISO Reconstructed and Original Signals

In addition, the spectrum of the lower frequency portions of the signals was analyzed to determine if any mode shape was missed in analysis. **Figure D.52** demonstrates the best and worst matches in the analysis, indicating that the mode shapes are an accurate depiction of the oscillation.

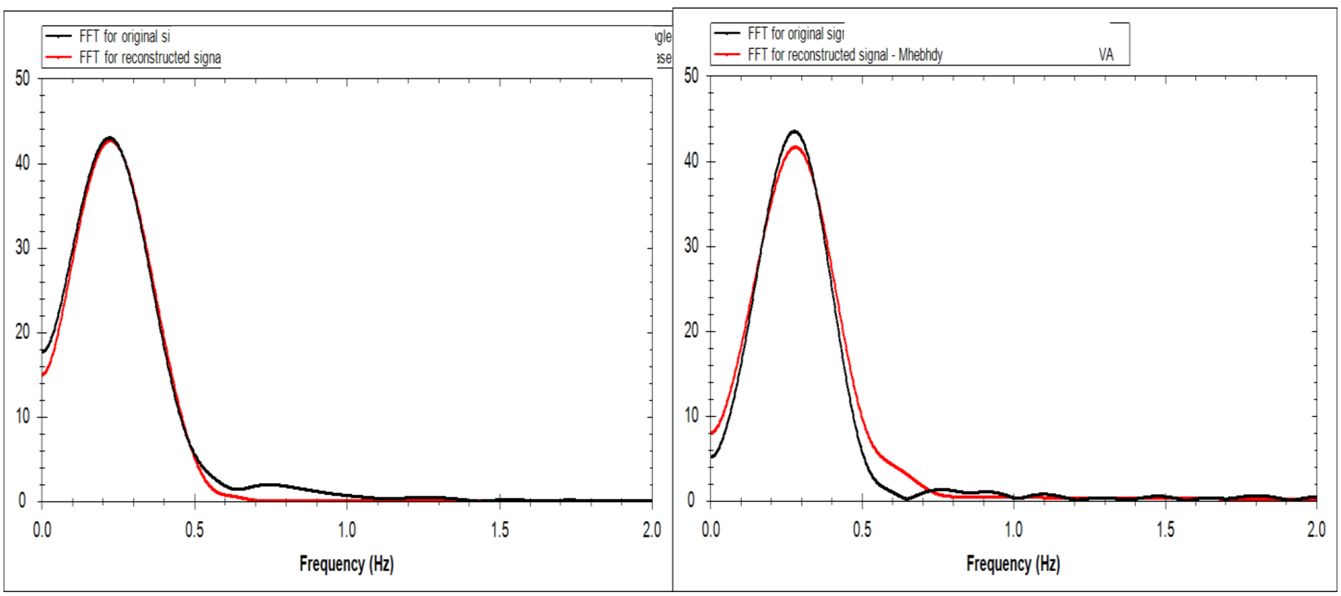

Figure D.52: Reconstructed and Original FFT Results. Left—Georgia, Right—MISO

Table D.4 provides the summary of the Matrix Pencil results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 144 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the Matrix Pencil analysis was 357 mHz. A link to the *Frequency Disturbance Report* can be found at the UTK website.[6]

Table D.4: Dominant Modes		
Frequency (Hz)	**Damping (%)**	**Total Energy (%)**
0.31	12.9	72
0.16	7.8	21

The mode shapes for the listed modes in **Table D.4** can be found in **Figures D.53** and **D.54**. The 0.31 Hz mode demonstrates the characteristic of a north to south mode shape; however, the more east the region, the lower

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participation in the mode shape. I.e. MISO region has a stronger participation in this mode shape rather than the NY ISO region. In the 0.16 Hz mode, we see that same north to south mode shape; however, the clustering of the north and south participation factors are tighter than the 0.31 Hz mode. Thus, there is stronger participation in the mode shape for the southern region in the 0.16 Hz mode rather than the 0.31 Hz mode.

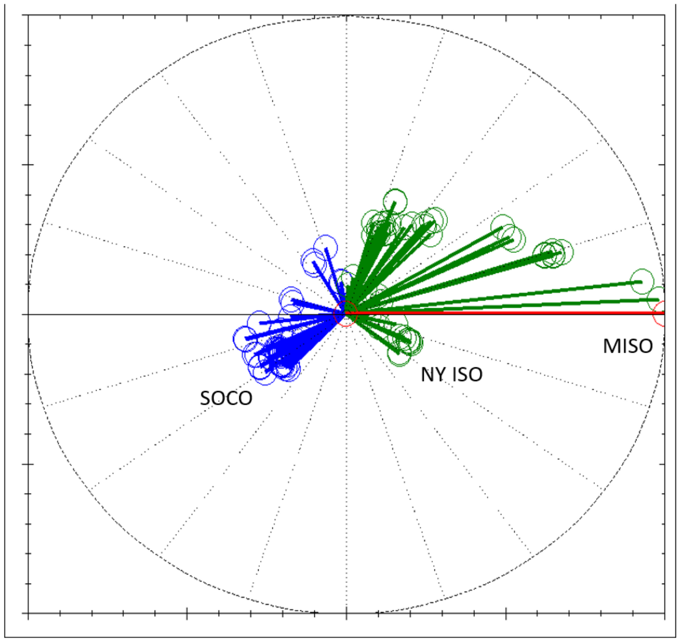

Figure D.53: Mode Shape for 0.31 Hz Mode

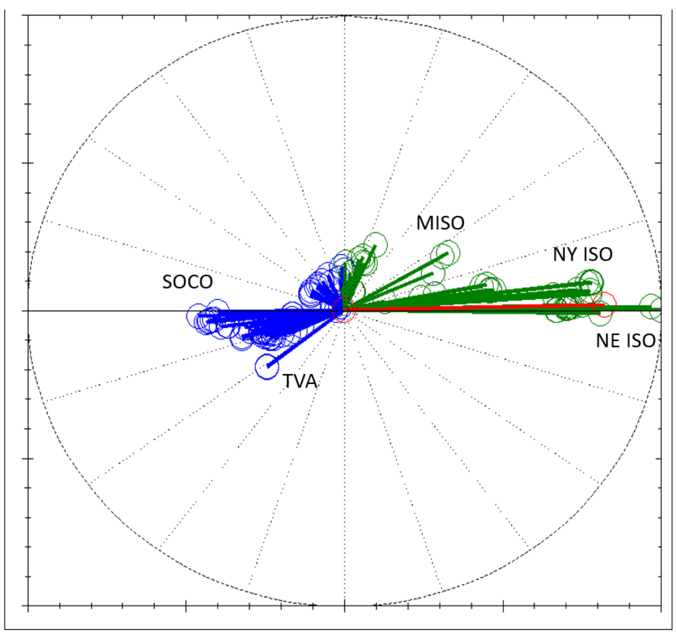

Figure D.54: Mode Shape for 0.16 Hz Mode

Event 7: 2017-03-16 16:11:45 UTC

This event involved a resource loss estimated at 870 MW tripping off-line. The system frequency response is shown in **Figure D.53**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

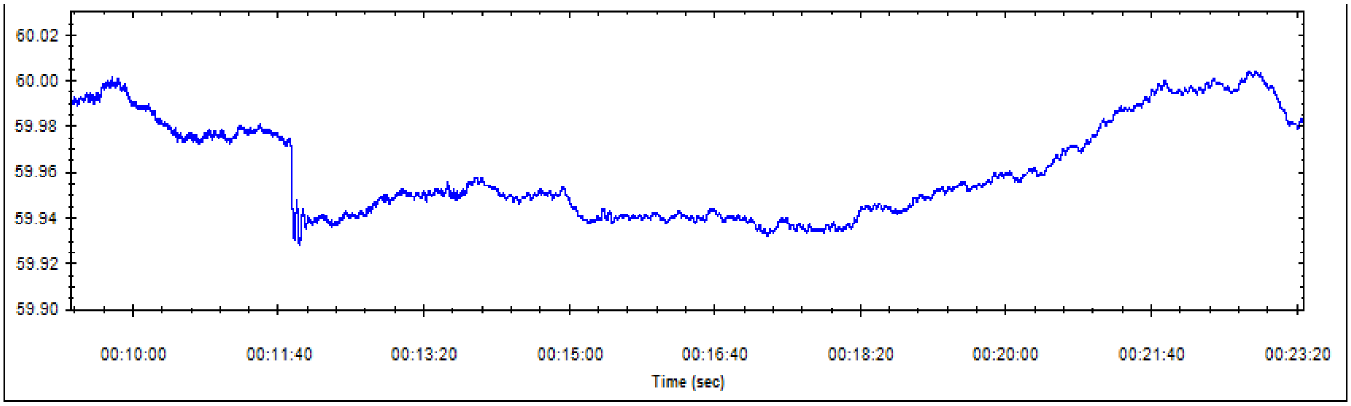

Figure D.55: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures D.56–D.58**.

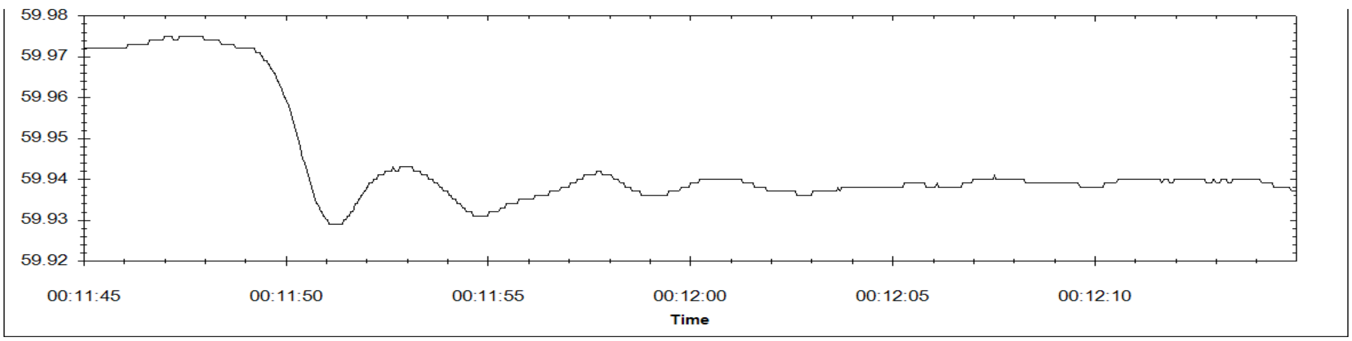

Figure D.56: New England area Frequency Signal

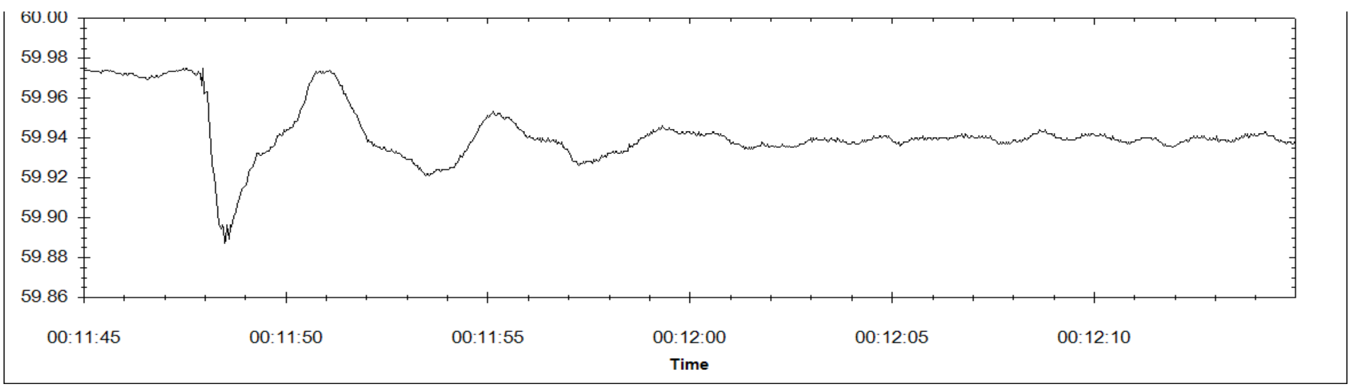

Figure D.57: MISO area Frequency Signal

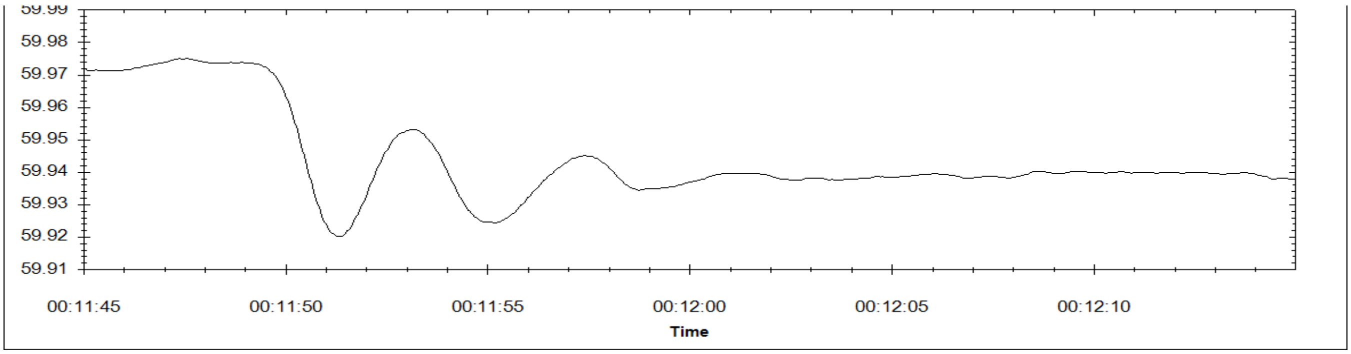

Figure D.58: Florida area Frequency Signal

To fit the ringdown analysis to the event, the analyzers utilized the bus frequency signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:09:56 to 00:10:03 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:11:45. The analysis window is demonstrated in **Figure D.59.**

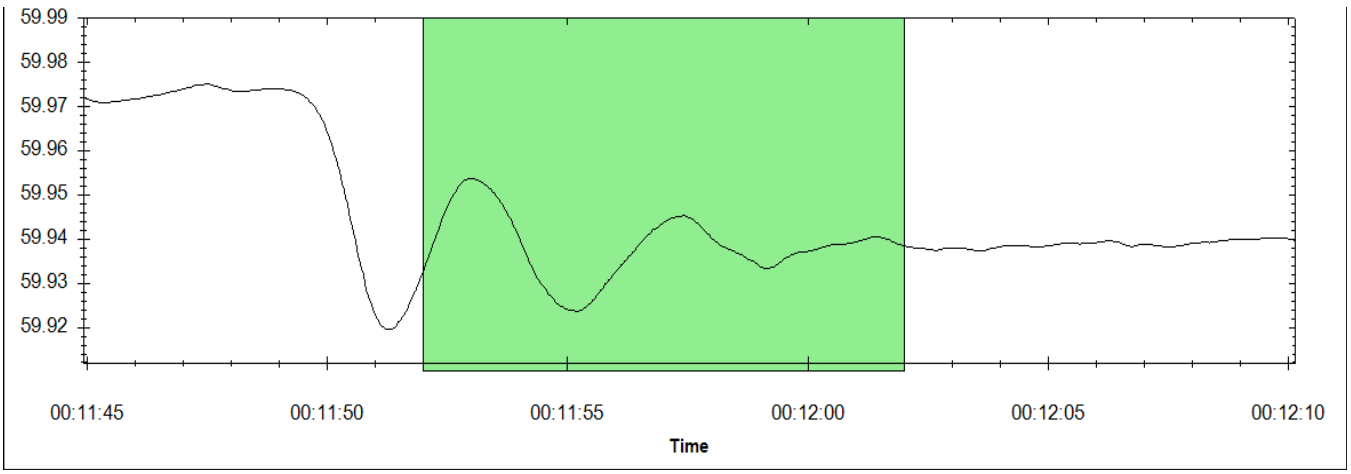

Figure D.59: Ringdown Analysis Window from 00:11:52 to 00:12:02

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures D.60**– **D.62** demonstrate the signal match between the original signal and reconstructed signal.

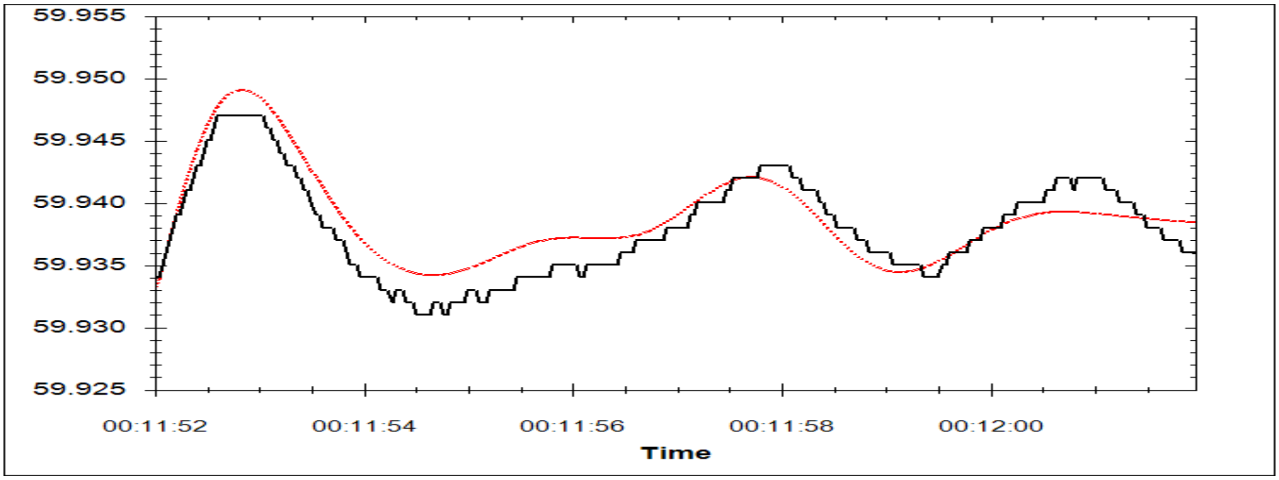

Figure D.60: New England Reconstructed and Original Signals

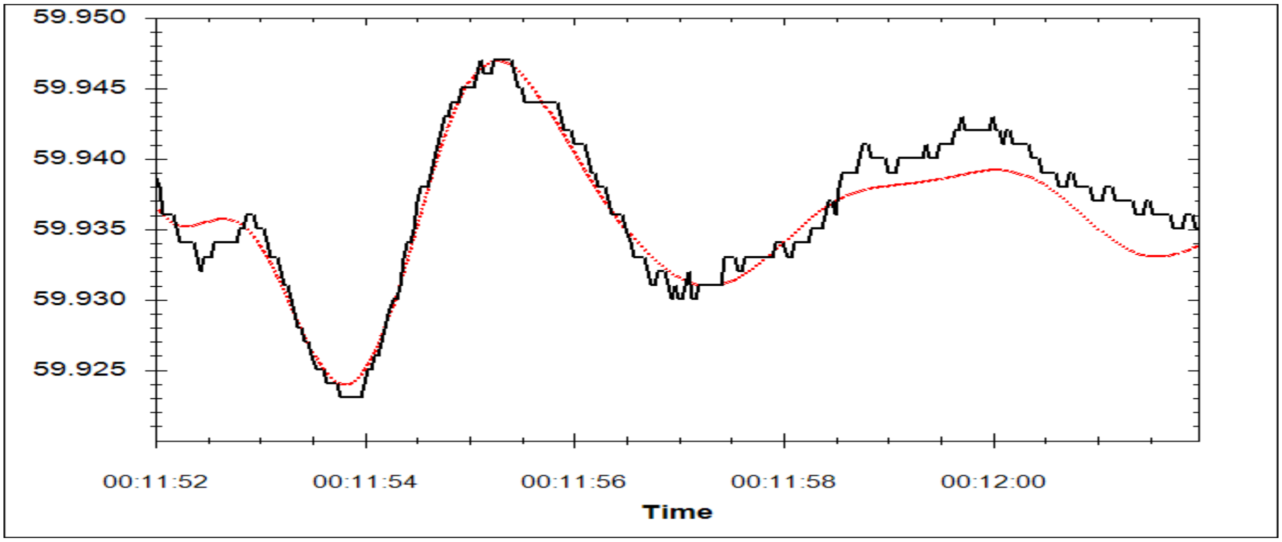

Figure D.61: MISO Reconstructed and Original Signals

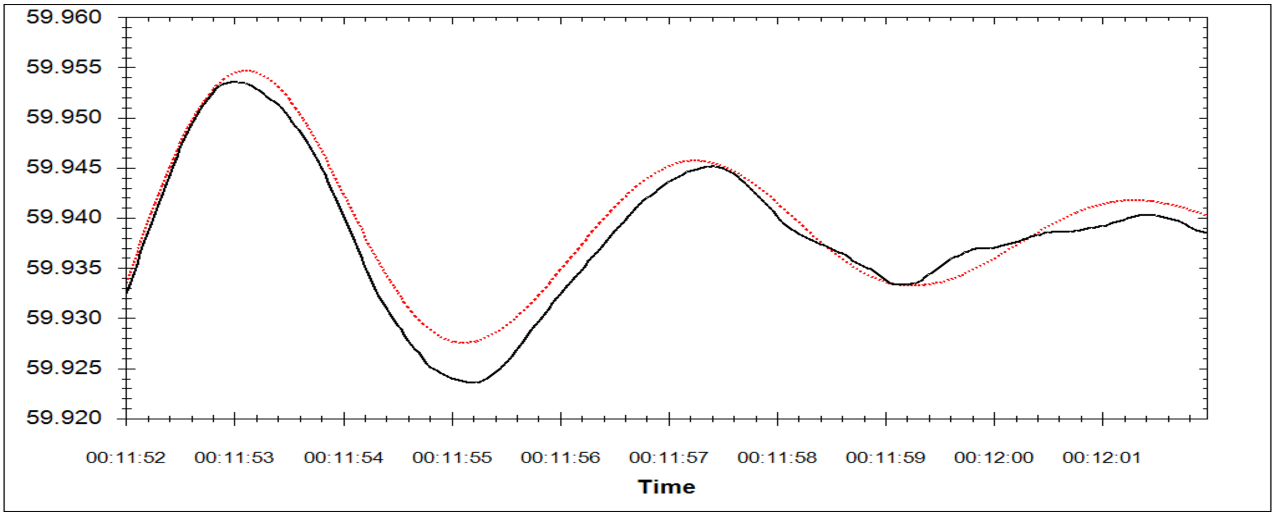

Figure D.62: Florida Reconstructed and Original Signals

In addition, the spectrum of the lower frequency portions of the signals was analyzed to determine if any mode shape was missed in analysis. **Figure D.63** demonstrates the best and worst matches in the analysis, indicating that the mode shapes are an accurate depiction of the oscillation.

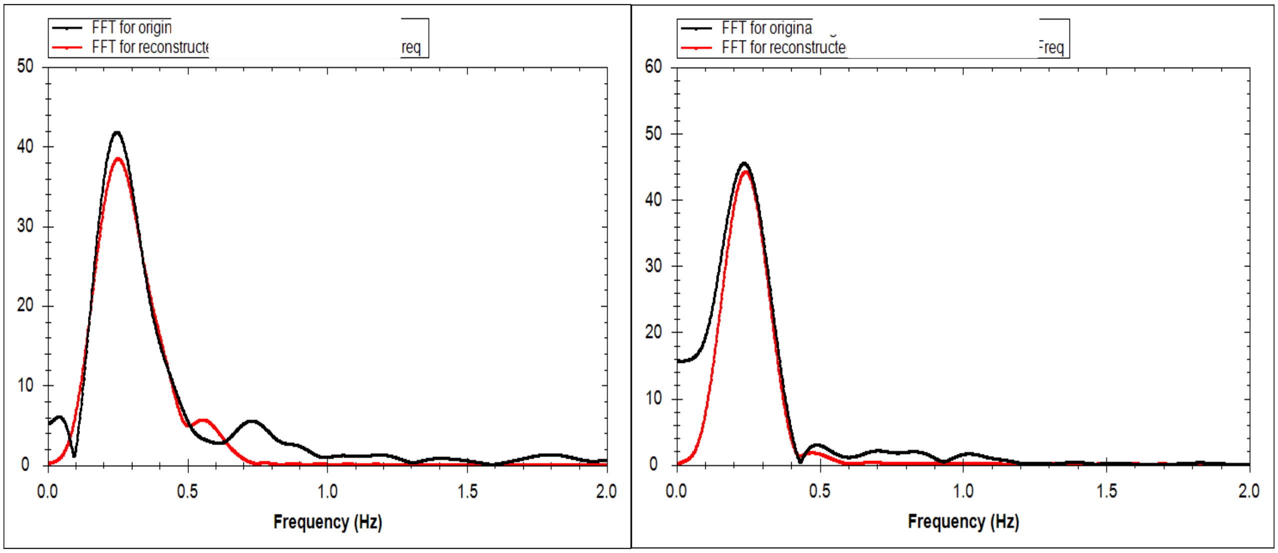

Figure D.63: Reconstructed and Original FFT Results. Left – MISO, Right – Florida

Table D.5 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 70 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the HTLS analysis was 357 mHz. A link to the *Frequency Disturbance Report* can be found at the UTK website.[7]

Table D.5: Dominant Modes		
Frequency (Hz)	Damping (%)	Total Energy (%)
0.24	12.2	87

The mode shapes for the listed modes in **Table D.5** can be found in **Figure D.64**. The 0.24 Hz mode shape demonstrates a strong participation in the Southern Atlantic and Northeastern United States Census regions against the West North Central United States Census Region of the Midwest. These identified regions have high participation factors and should monitor the damping ratio of this modal response as it propagates with respect to natural system events in these regions.

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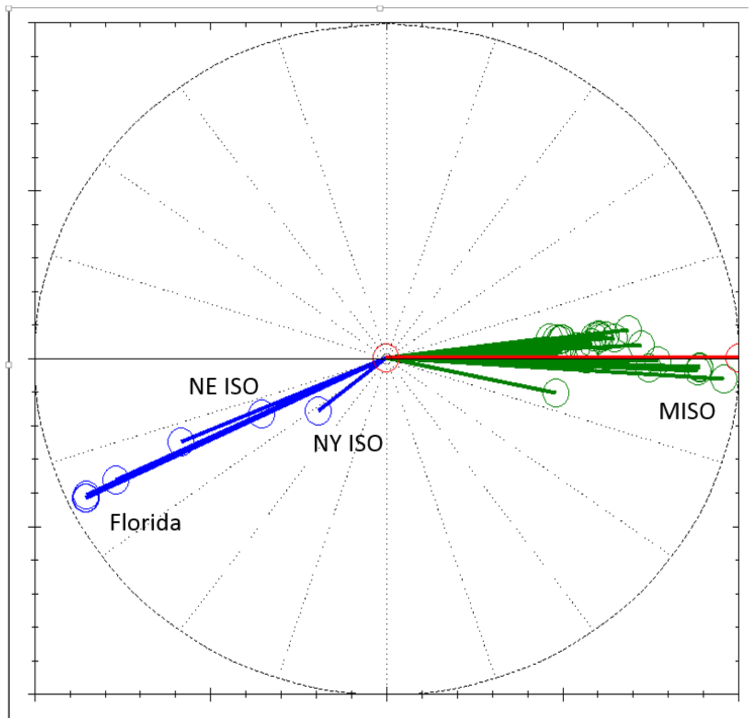

Figure D.64: Mode Shape for 0.24 Hz Mode

Appendix E: Texas Interconnection Analysis Results

For the analysis done in this Appendix, the references to the center point refer to an average of all the angle or frequency signals as is a commonly used approximation for the system center for PMU data. This approximation will dampen down signals close to this center for the mode shape phase.

Event 1: 2016-01-27 05:25:06 UTC

This event involved a resource loss estimated at 740 MW tripping off-line. The system frequency response is shown in **Figure E.1**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small “sizzle” in frequency is normal for continuous fluctuations in generation and load.

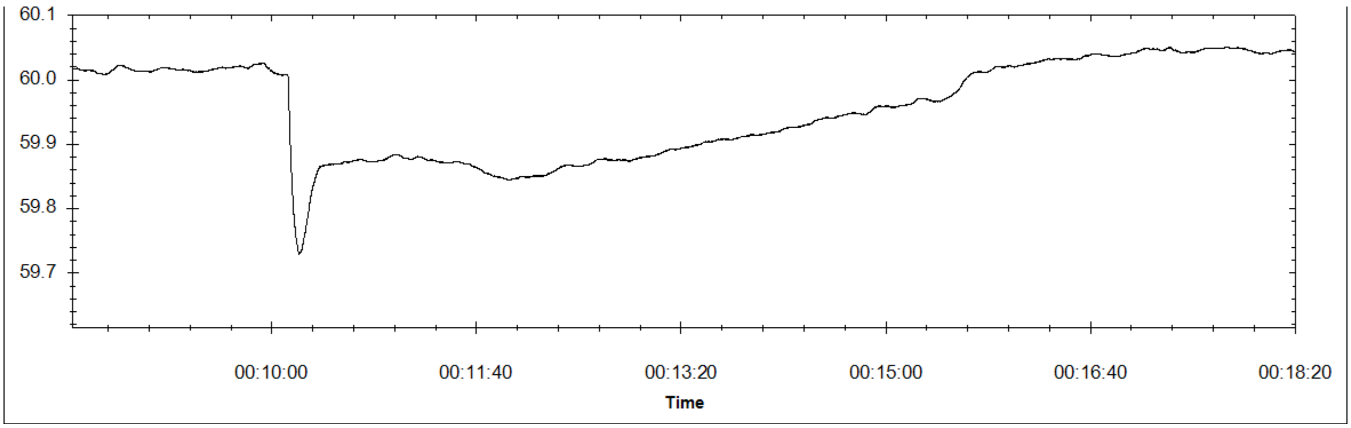

Figure E.1: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figure E.2** and **Figure E.3.**

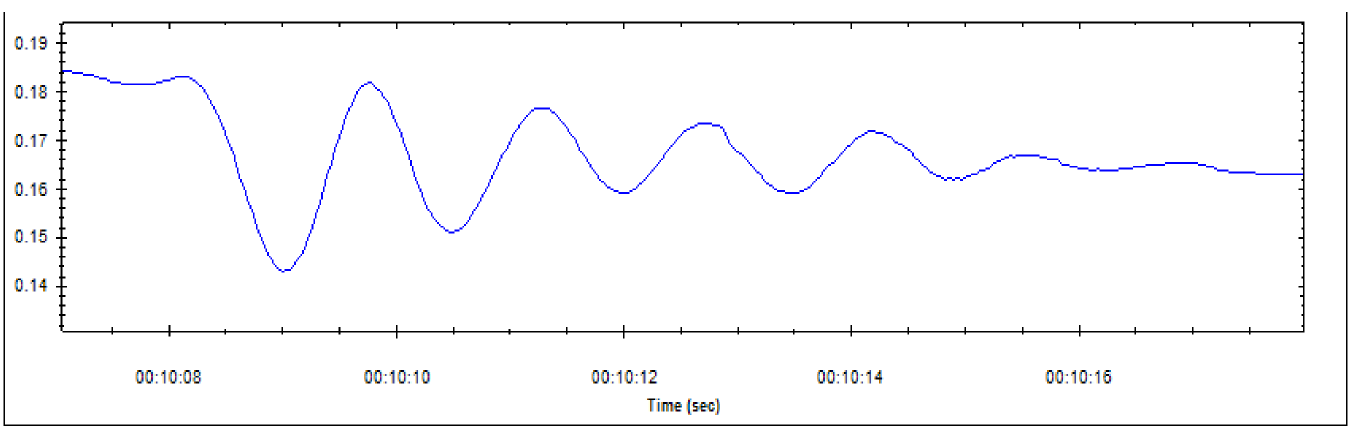

Figure E.2: South Texas Area Phase Angle with Respect to Center Point

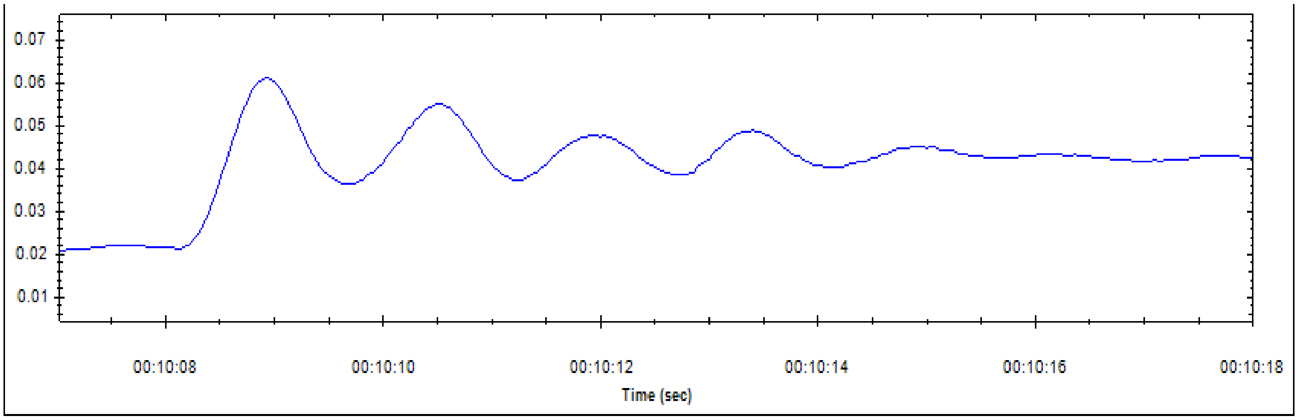

Figure E.3: North Texas Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the voltage phase angle signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:10:09 to 00:10:16 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:10:06. The analysis window is demonstrated in **Figure E.4.**

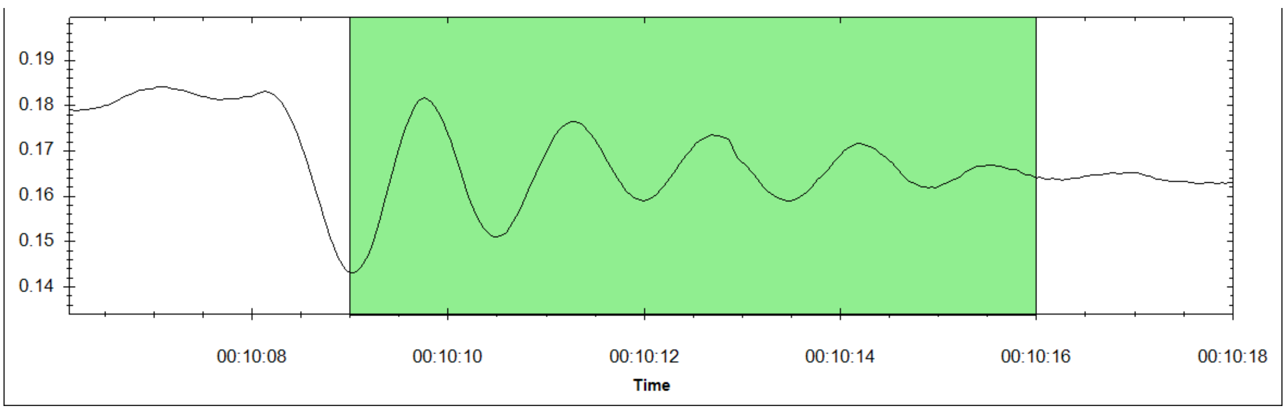

Figure E.4: Ringdown Analysis Window from 00:10:09 to 00:10:16

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures E.5** and **E.6** demonstrate the signal match between the original and reconstructed signals.

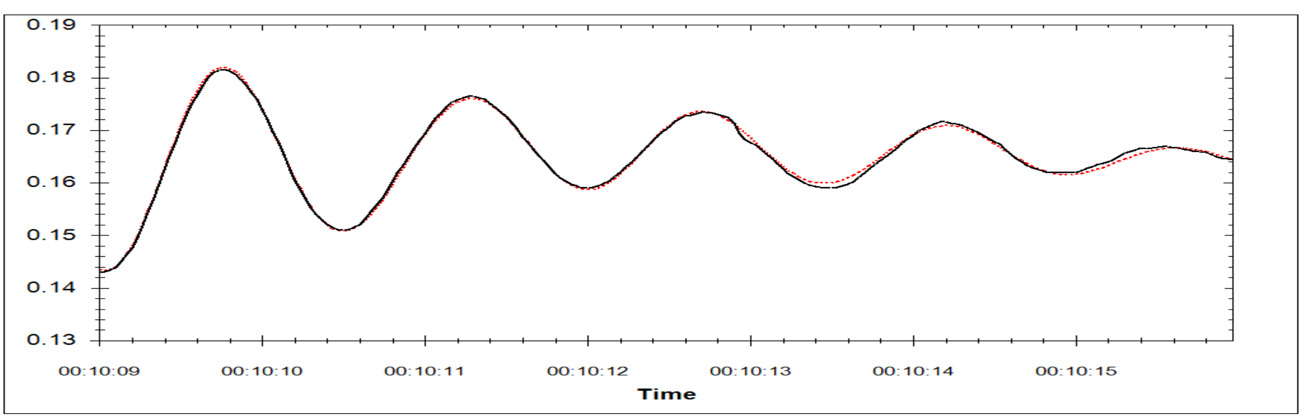

Figure E.5: South Texas Reconstructed and Original Signals

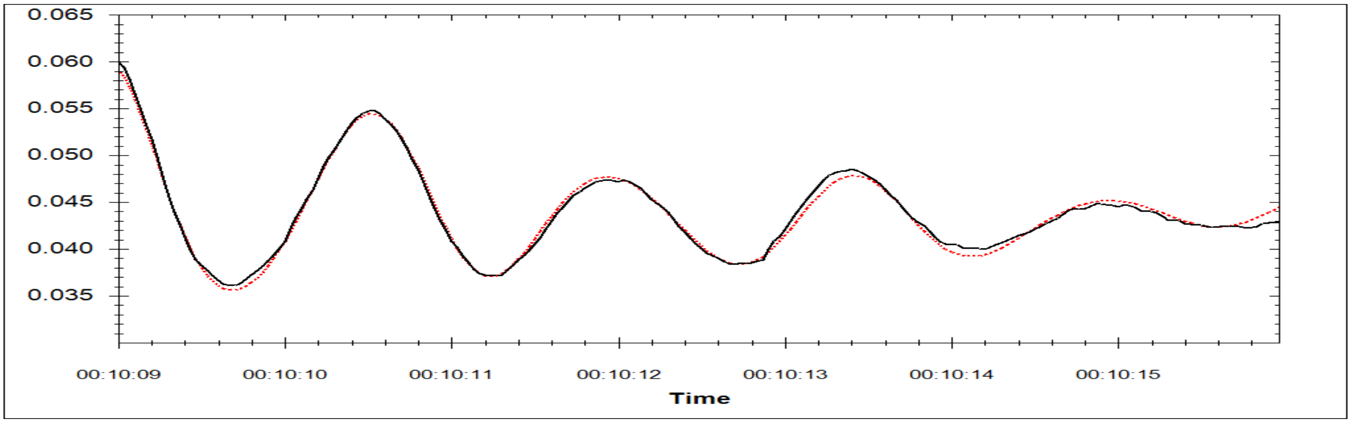

Figure E.6: North Texas Reconstructed and Original Signals

As the signals were such a good fit based on observation, no spectral analysis was taken to determine if other lower frequency modes were missed.

Table E.1 provides the summary of the Prony results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 13 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the Prony analysis was 3 mHz. A link to the *Frequency Disturbance Report* can be found at the UTK website.[8]

Table E.1: Dominant Modes		
Frequency (Hz)	Damping (%)	Total Energy (%)
0.68	7	96

The mode shapes for the listed mode in Table E.1 can be found in Figure E.7. The 0.68 Hz mode demonstrates a North Texas to South Texas mode shape. With the small amount of signals used for this analysis, it makes it hard to fully understand the 0.68 Hz mode shape, and other events with more signals will provide a more accurate depiction for the mode shape.

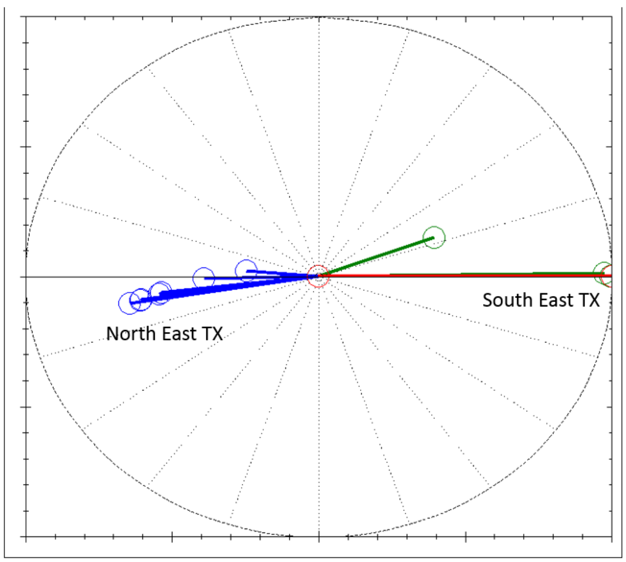

Figure E.7: Mode Shape for 0.68 Hz Mode

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Event 2: 2016-04-18 04:30:42 UTC

This event involved a resource loss estimated at 520 MW tripping off-line. The system frequency response is shown in **Figure E.8**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

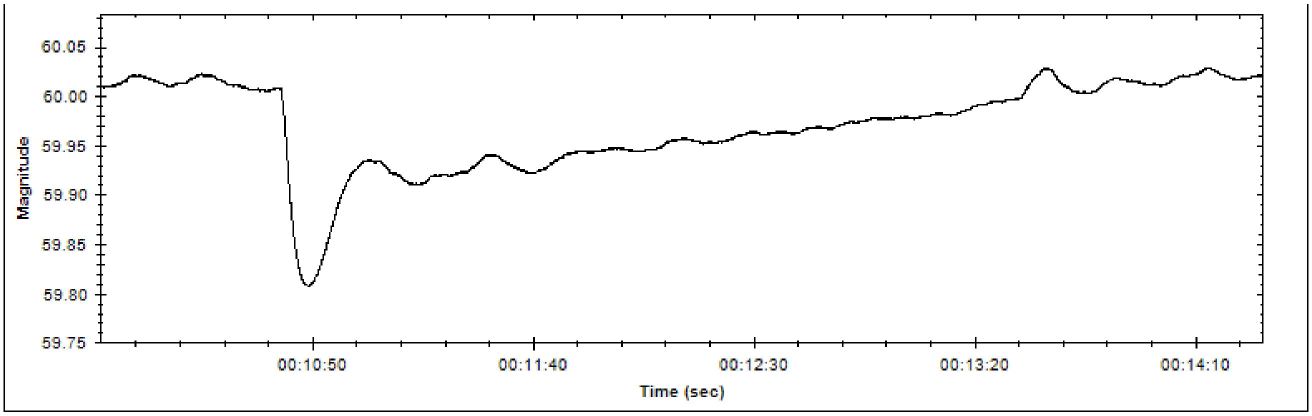

Figure E.8: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figure E.9** and **Figure E.10.**

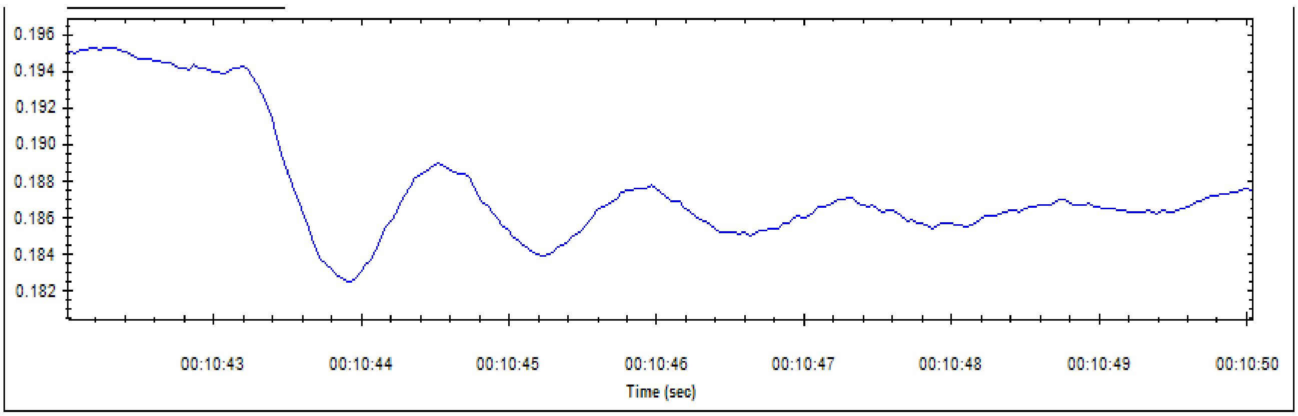

Figure E.9: South Texas Area Phase Angle with Respect to Center Point

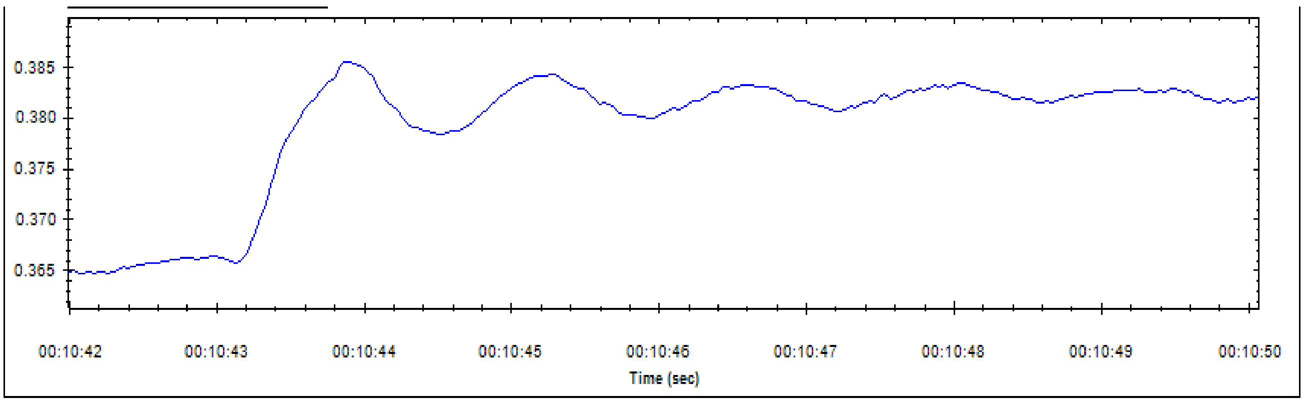

Figure E.10: North Texas Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the voltage phase angle signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:10:44 to 00:10:49 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:10:42. The analysis window is demonstrated in **Figure E.11**.

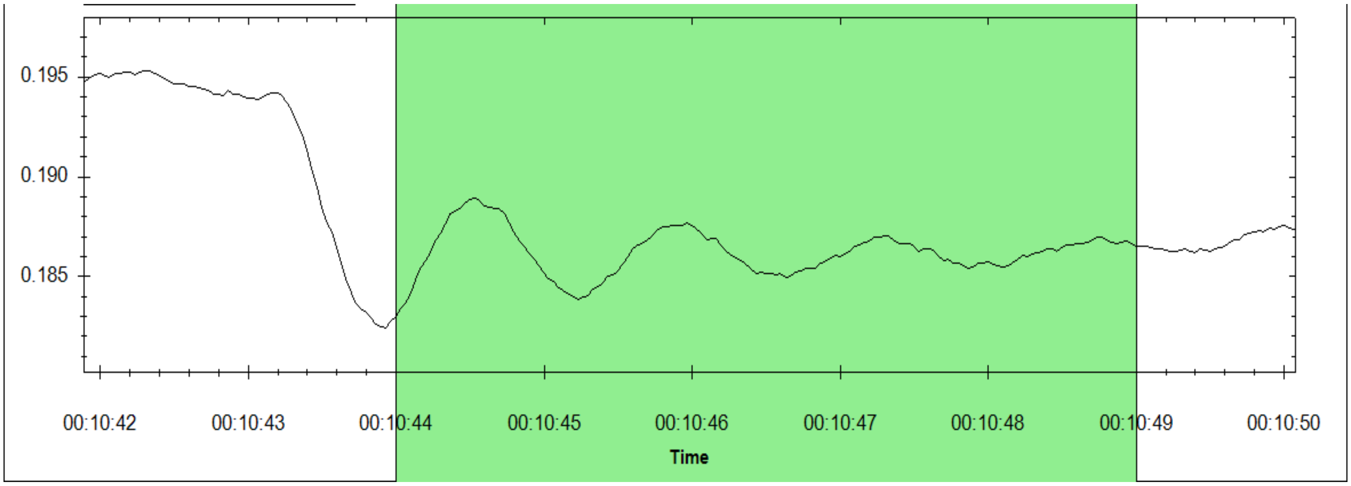

Figure E.11: Ringdown Analysis Window from 00:10:44 to 00:10:49

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures E.12** and **E.13** demonstrate the signal match between the original and reconstructed signals.

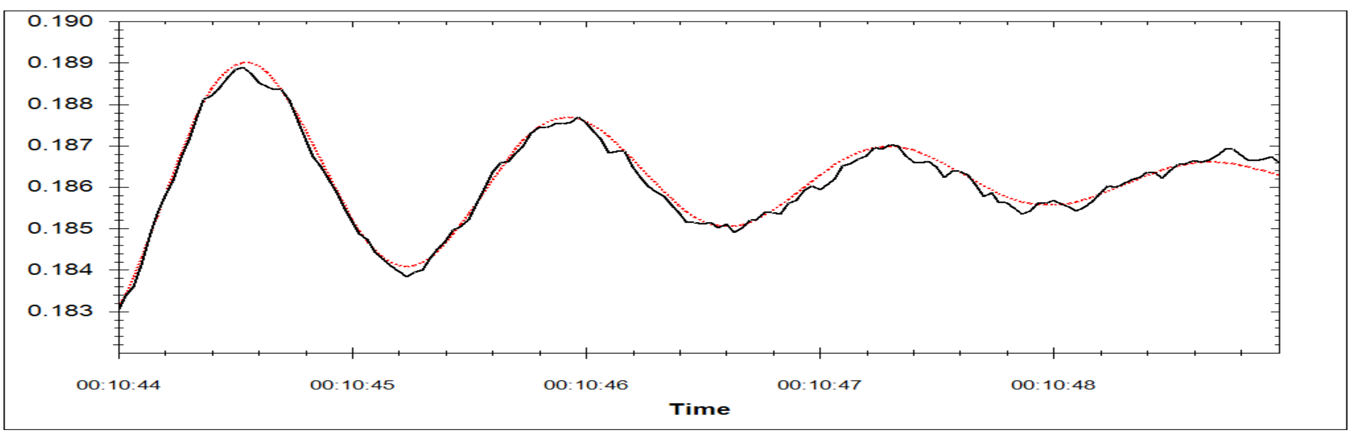

Figure E.12: South Texas Reconstructed and Original Signals

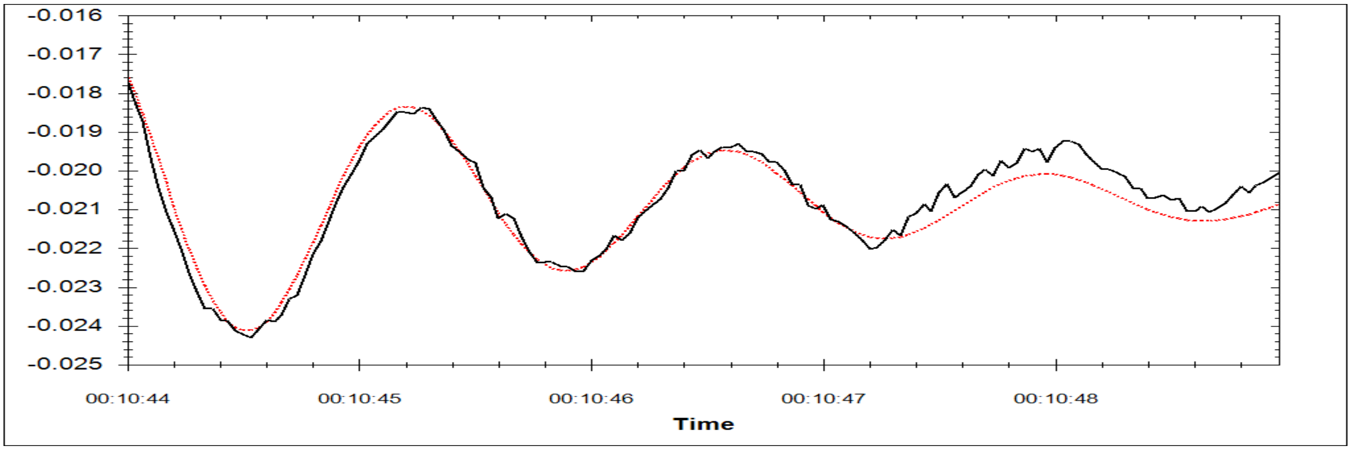

Figure E.13: North Texas Reconstructed and Original Signals

As the signals were such a good fit based on observation, no spectral analysis was taken to determine if other lower frequency modes were missed.

Table E.2 provides the summary of the Prony results from the analysis. Modes with a relative energy less than 10% are not shown. A total of eight signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the Prony analysis was 22 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[9]

Table E.2: Dominant Modes

Frequency (Hz)	Damping (%)	Total Energy (%)
0.73	9.9	100

The mode shapes for the listed mode in **Table E.2** can be found in **Figure E.14.** The 0.73 Hz mode demonstrates a North to South Texas mode shape. With the small amount of signals used for this analysis, it makes it hard to fully understand the 0.73 Hz mode shape, and other events with more signals will provide a more accurate depiction for the mode shape. In addition, this event had some data quality issues that further reduced the available signals for analysis. Care should be taken in interpreting the results from the data provided by this event as the amount of signals here are not a substantive sampling of the Interconnection.

[9] Frequency Disturbance Report

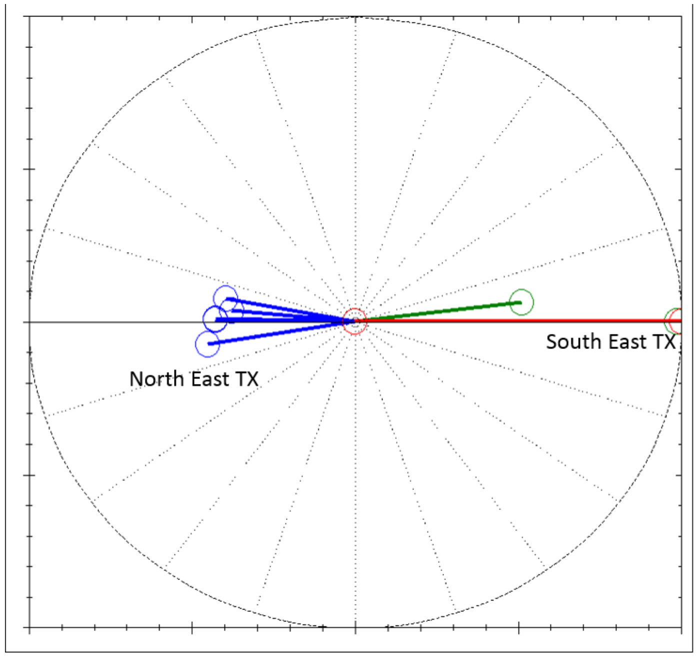

Figure E.14: Mode Shape for 0.73 Hz Mode

Event 3: 2016-07-10 23:54:21 UTC

This event involved a resource loss estimated at 500 MW tripping off-line. The system frequency response is shown in **Figure E.15**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

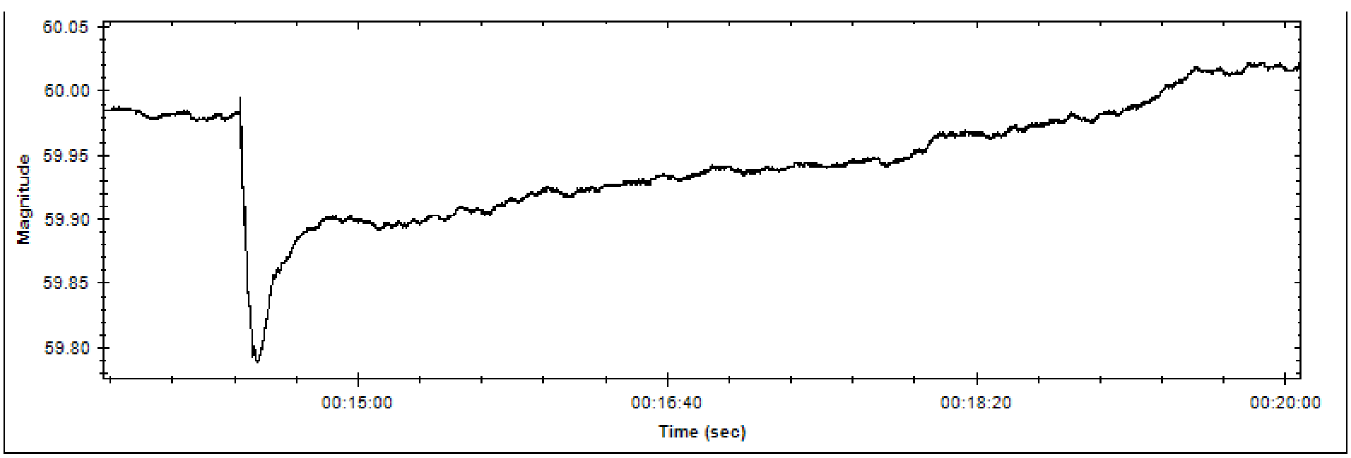

Figure E.15: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figure E.16** and **Figure E.17**

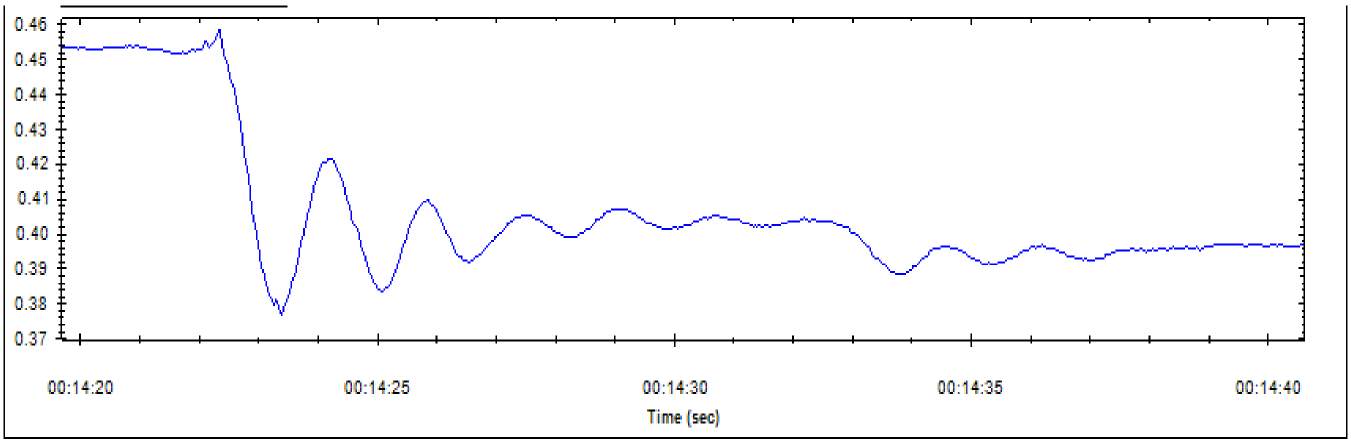

Figure E.16: South Texas Area Phase Angle with Respect to Center Point

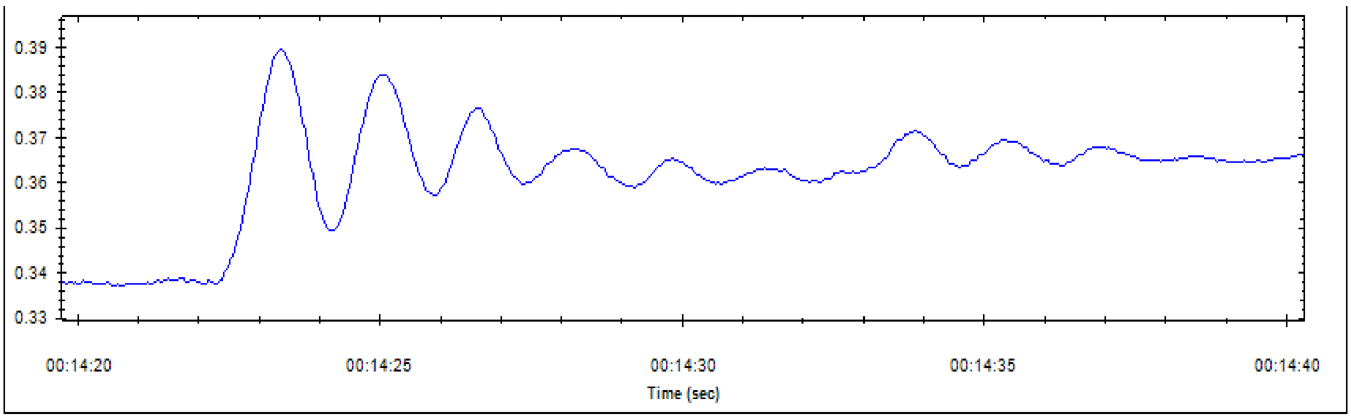

Figure E.17: North Texas Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the voltage phase angle signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:14:25 to 00:14:30 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:14:21. The analysis window is demonstrated in **Figure E.18.**

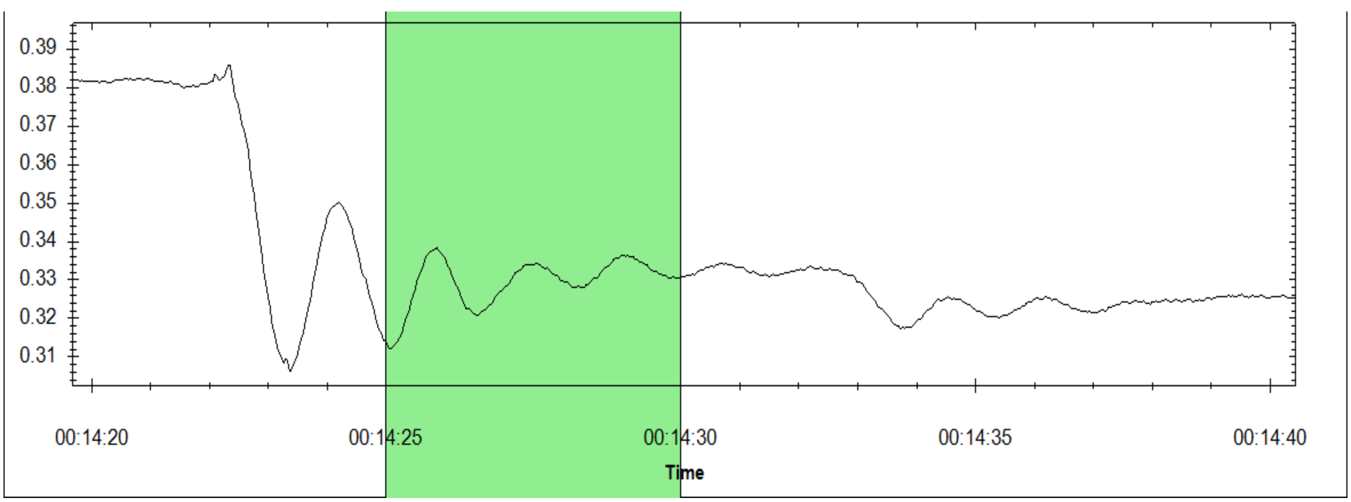

Figure E.18: Ringdown Analysis Window from 00:14:25 to 00:14:30

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures E.19** and **E.20** demonstrate the signal match between the original and reconstructed signals.

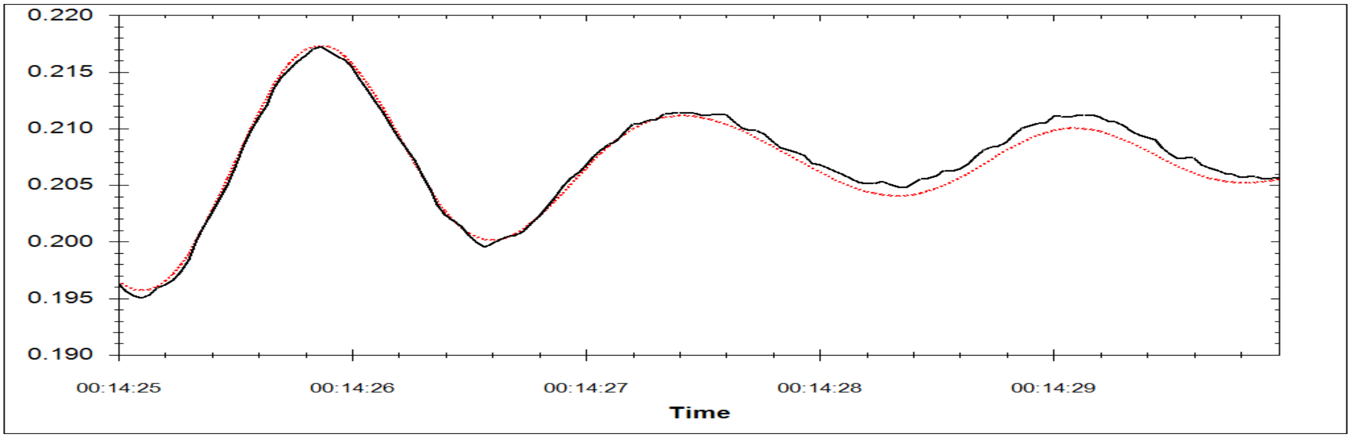

Figure E.19: South Texas Reconstructed and Original Signals

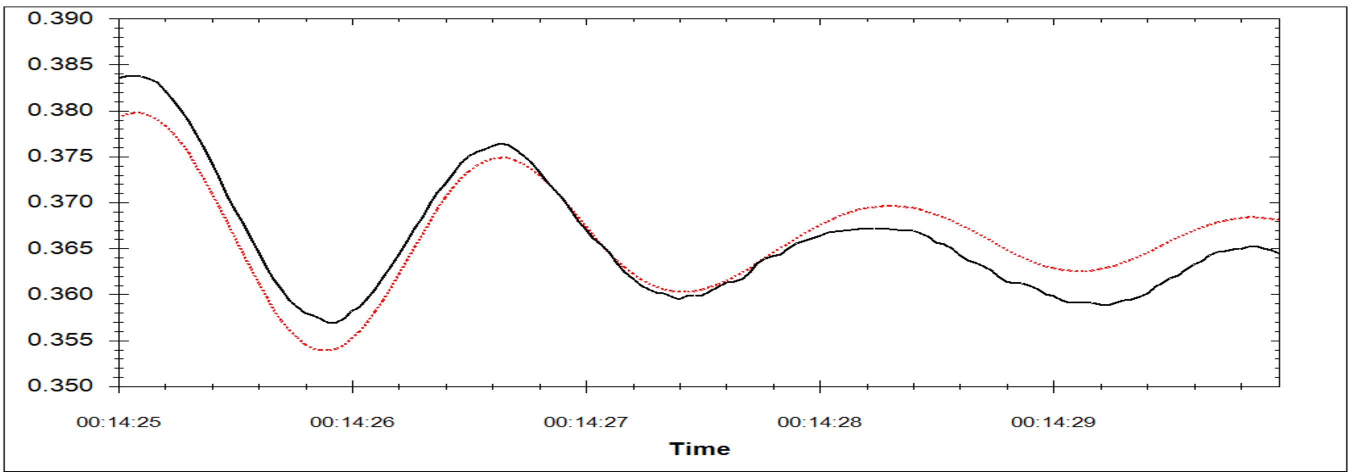

Figure E.20: North Texas Reconstructed and Original Signals

As the signals were such a good fit based on observation, no spectral analysis was taken to determine if other lower frequency modes were missed.

Table E.3 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of eight signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the HTLS analysis was 23 mHz. A link to the *Frequency Disturbance Report* can be found at the UTK website.[10]

Table E.3: Dominant Modes

Frequency (Hz)	Damping (%)	Total Energy (%)
0.62	10.2	98

[10] Frequency Disturbance Report

The mode shapes for the listed mode in **Table E.3** can be found in **Figure E.21**. The 0.73 Hz mode demonstrates a North Texas to South Texas mode shape. With the small amount of signals used for this analysis, it makes it hard to fully understand the 0.62 Hz mode shape, and other events with more signals will provide a more accurate depiction for the mode shape. In addition, this event had some data quality issues that further reduced the available signals for analysis. Care should be taken in interpreting the results from the data provided by this event as the amount of signals here are not a substantive sampling of the Interconnection.

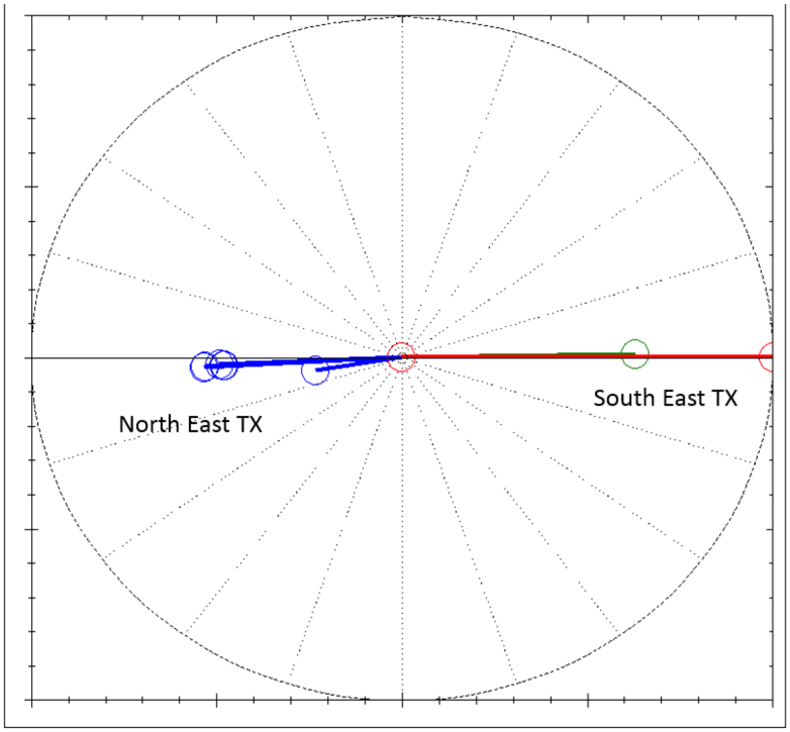

Figure E.21: Mode Shape for 0.62 Hz Mode

Event 4: 2016-10-23 19:34:35 UTC

This event involved a resource loss estimated at 360 MW tripping off-line. The system frequency response is shown in **Figure E.22.** The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

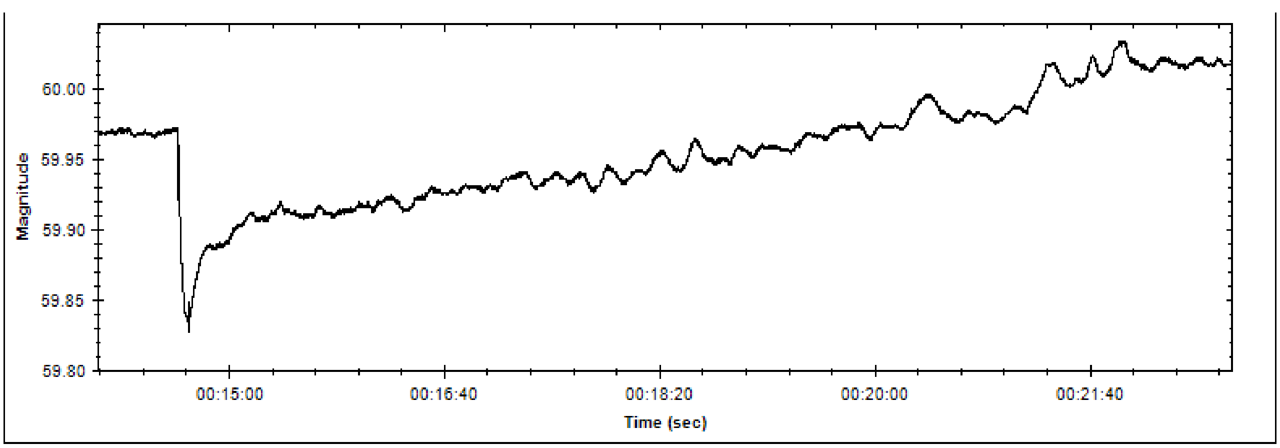

Figure E.22: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figure E.23** and **Figure E.24.**

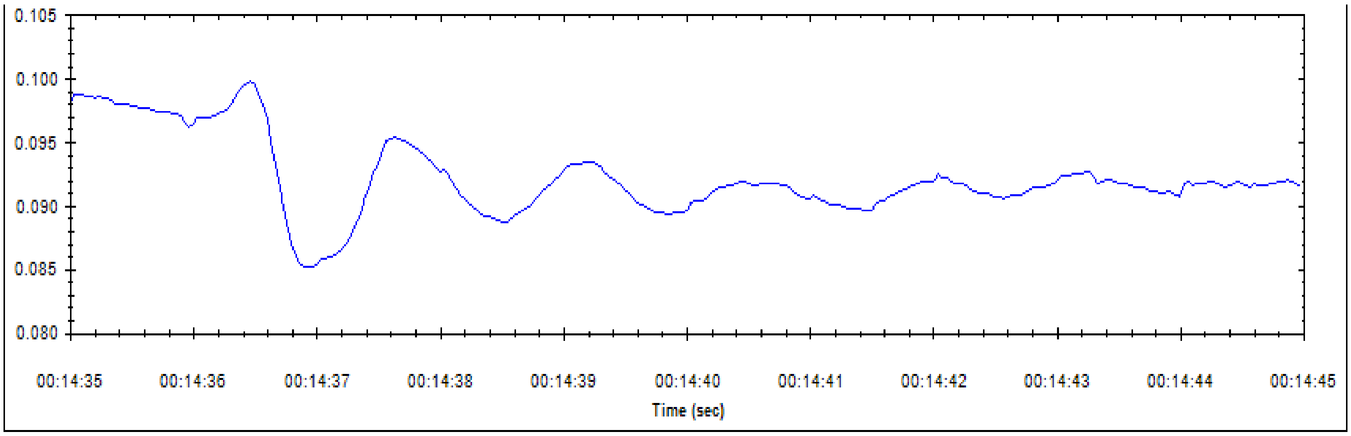

Figure E.23: South Texas Area Phase Angle with Respect to Center Point

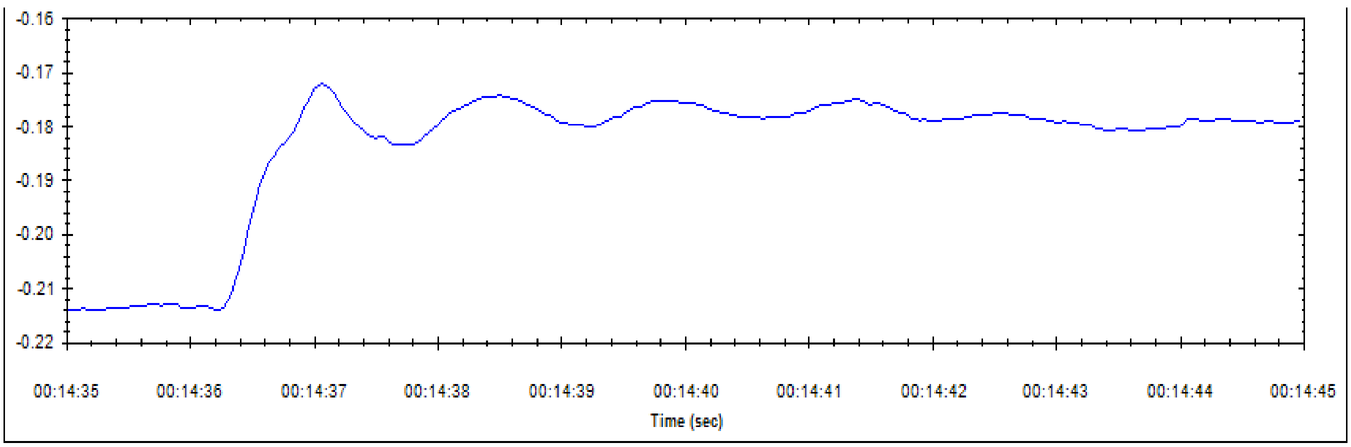

Figure E.24: North Texas Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the voltage phase angle signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:14:37 to 00:14:42 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:14:35. The analysis window is demonstrated in **Figure E.25.**

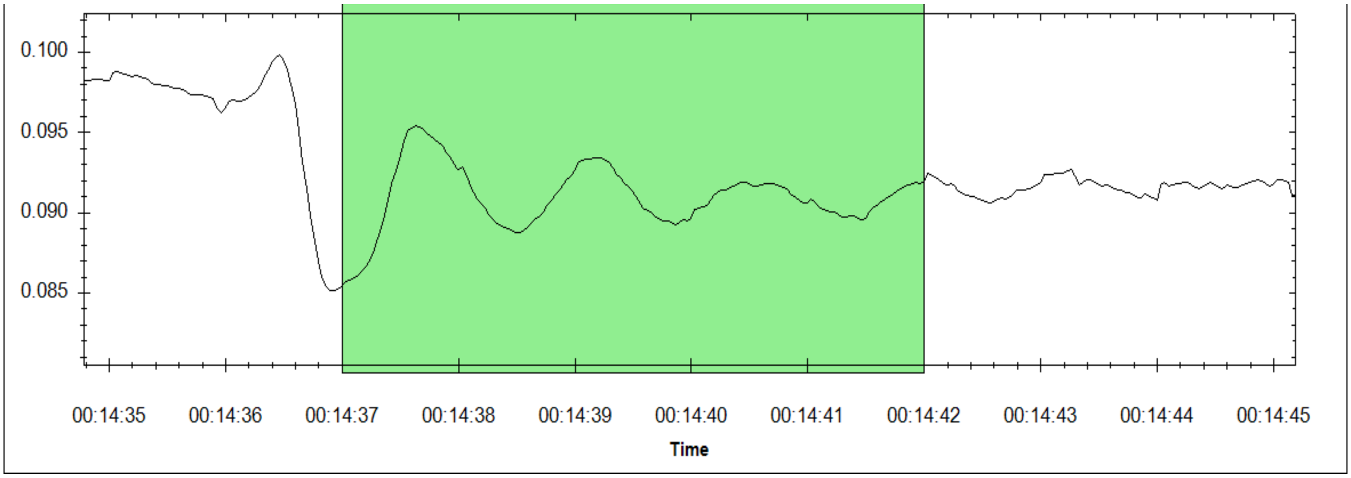

Figure E.25: Ringdown Analysis Window from 00:14:37 to 00:14:42

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures E.26** and **E.27** demonstrate the signal match between the original and reconstructed signals.

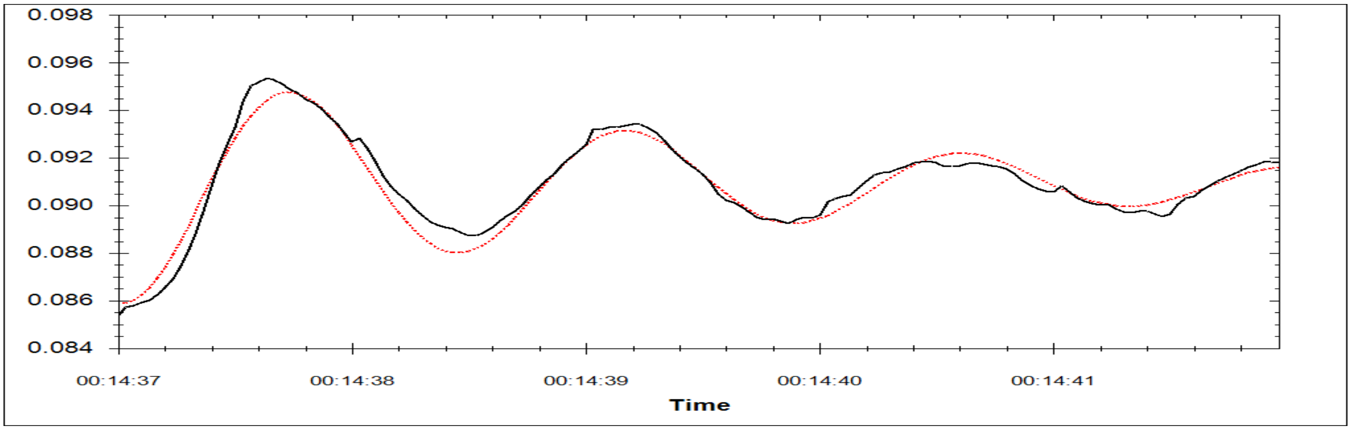

Figure E.26: South Texas Reconstructed and Original Signals

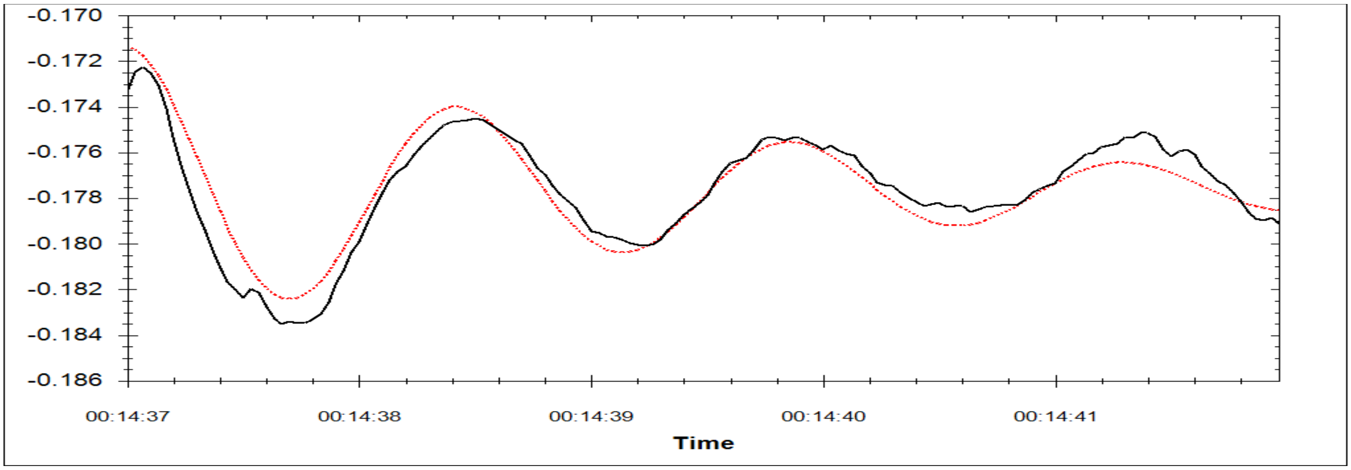

Figure E.27: North Texas Reconstructed and Original Signals

As the signals were such a good fit based on observation, no spectral analysis was taken to determine if other lower frequency modes were missed.

Table E.4 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of six signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the HTLS analysis was 20 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[11]

Table E.4: Dominant Modes		
Frequency (Hz)	Damping (%)	Total Energy (%)
0.70	8.2	100

The mode shapes for the listed mode in **Table E.4** can be found in **Figure E.28**. The 0.73 Hz mode demonstrates a North Texas to South Texas mode shape. With the small amount of signals used for this analysis, it makes it hard to fully understand the 0.62 Hz mode shape, and other events with more signals will provide a more accurate depiction for the mode shape. In addition, this event had some data quality issues that further reduced the available signals for analysis, and even then the resulting signals are plagued by nonlinearities and quality issues that could cause errors in interpreting the results from the data provided by this event as the amount of signals here are not a substantive sampling of the Interconnection.

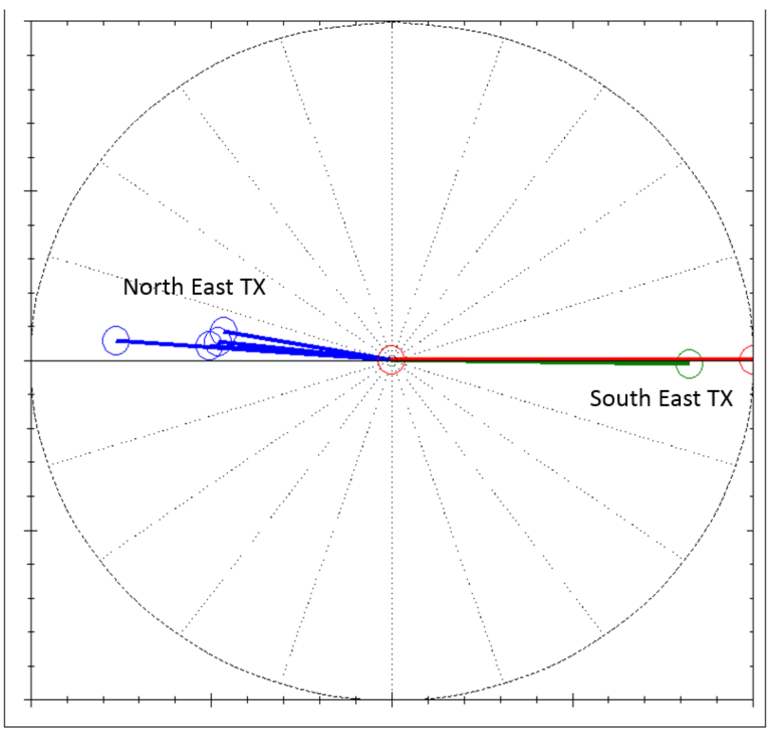

Figure E.28: Mode shape for 0.70 Hz Mode

Event 5: 2017-03-10 00:36:46 UTC

This event involved a resource loss estimated at 850 MW tripping off-line. The system frequency response is shown in **Figure E.29.** The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small “sizzle” in frequency is normal for continuous fluctuations in generation and load.

[11] Frequency Disturbance Report

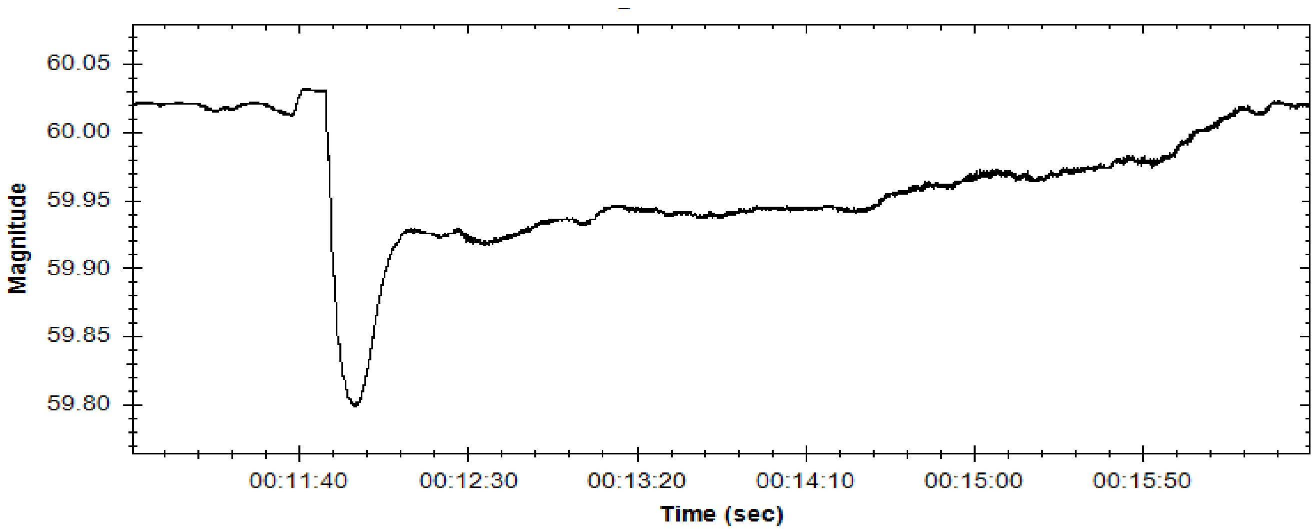

Figure E.29: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figure E.30** and **Figure E.31.**

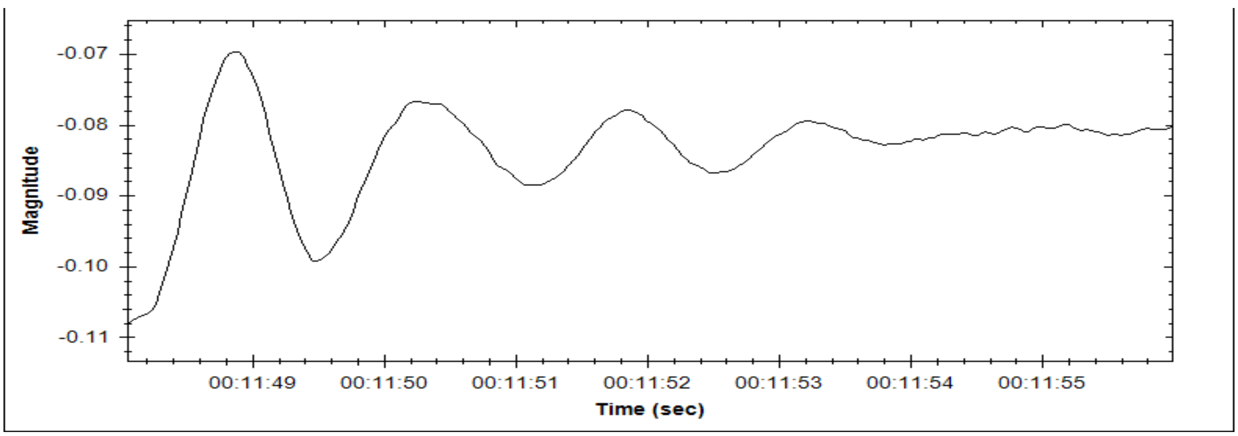

Figure E.30: South Texas Area Phase Angle with Respect to Center Point

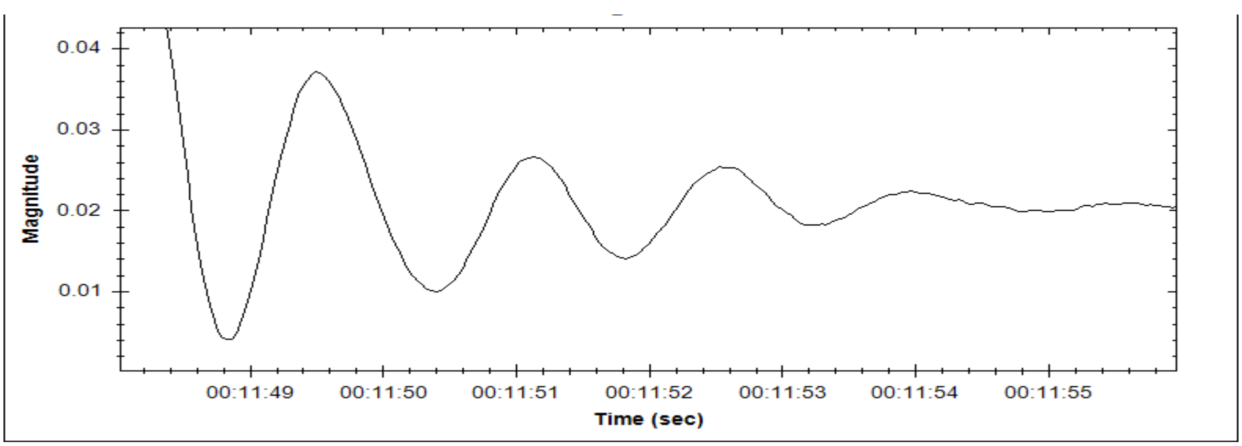

Figure E.31: North Texas Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the voltage phase angle signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:11:49 to 00:11:56 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:11:46. The analysis window is demonstrated in **Figure E.32**.

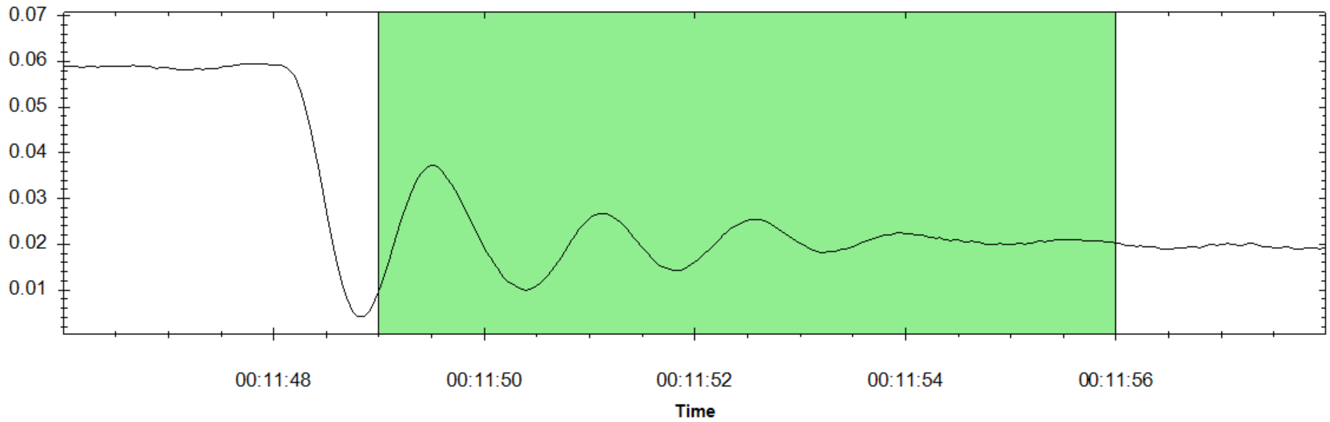

Figure E.32: Ringdown Analysis Window from 00:11:49 to 00:11:56

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures E.33** and **E.34** demonstrate the signal match between the original and reconstructed signals.

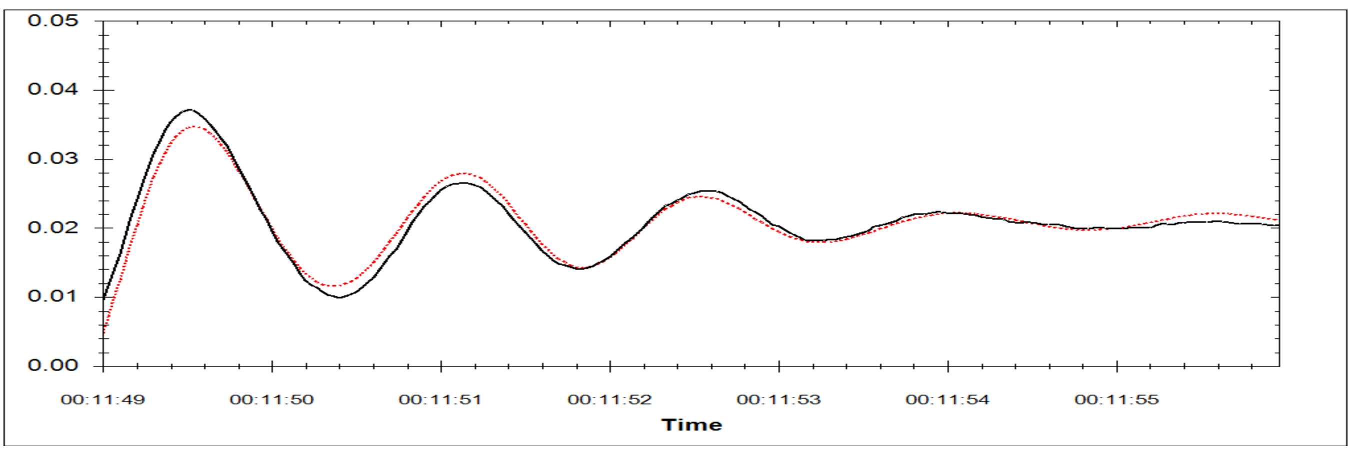

Figure E.33: South Texas Reconstructed and Original Signals

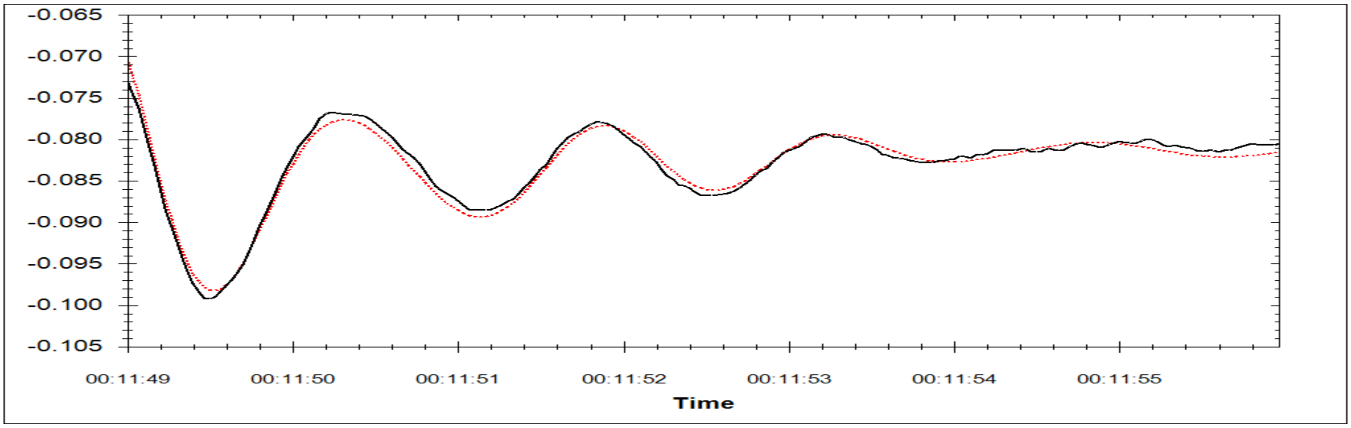

Figure E.34: North Texas Reconstructed and Original Signals

As the signals were such a good fit based on observation, no spectral analysis was taken to determine if other lower frequency modes were missed.

Table E.5 provides the summary of the Prony results from the analysis. Modes with a relative energy less than 10% are not shown. A total of seven signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the Prony analysis was 14 mHz. A link to the *Frequency Disturbance Report* can be found here.

Table E.5: Dominant Modes		
Frequency (Hz)	Damping (%)	Total Energy (%)
0.67	11	95

The mode shapes for the listed mode in **Table E.5** can be found in **Figure E.35**. The 0.73 Hz mode demonstrates a North Texas to South Texas mode shape. With the small amount of signals used for this analysis, it makes it hard to fully understand the 0.67 Hz mode shape, and other events with more signals will provide a more accurate depiction for the mode shape. In addition, this event had some signals that contained major nonlinear responses that would cause errors when trying to do linear ringdown analysis on the events.

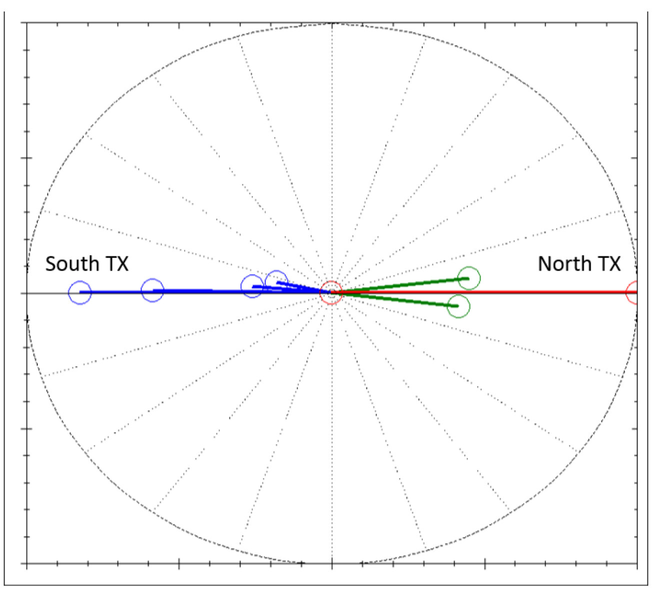

Figure E.35: Mode Shape for 0.67 Hz Mode

Appendix F: Western Interconnection Analysis Results

For the analysis done in this section, the references to the center point refer to a bus near the California-Oregon Intertie (COI), which was chosen as it is close to an electromechanical center to the Western Interconnection (WI). This reference may impact the mode shape behavior for PMU signals originating near the COI due to how the analysis tool was initialized.

Event 1: 2016-01-21 09:08:53 UTC

This event involved a resource loss estimated at 960 MW tripping off-line. The system frequency response is shown in **Figure F.1**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load. In this event, there was also seen a strong response from a localized mode in the Montana region depicted in **Figure F.2.**

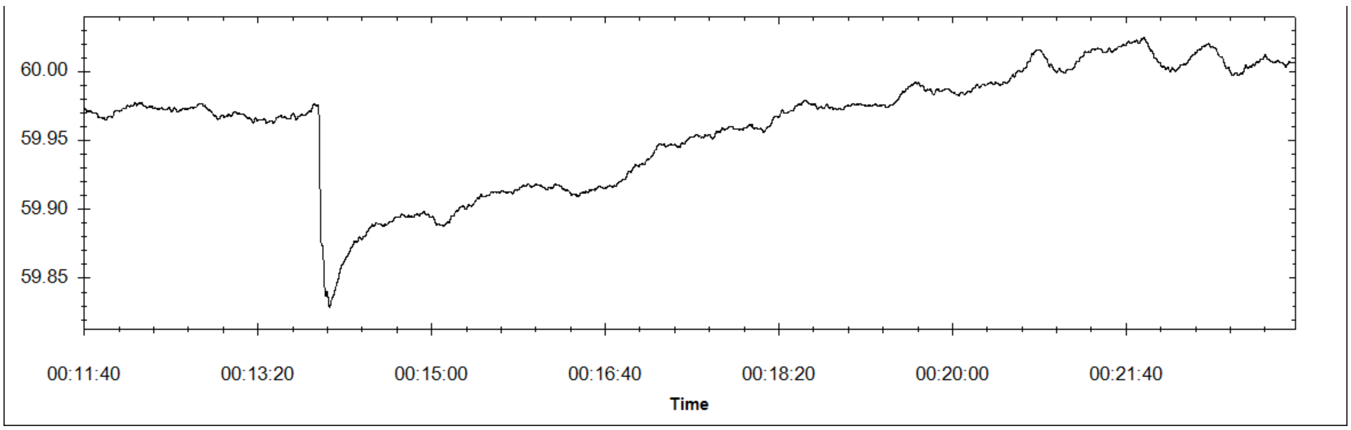

Figure F.1: PMU Frequency Measurement during Disturbance

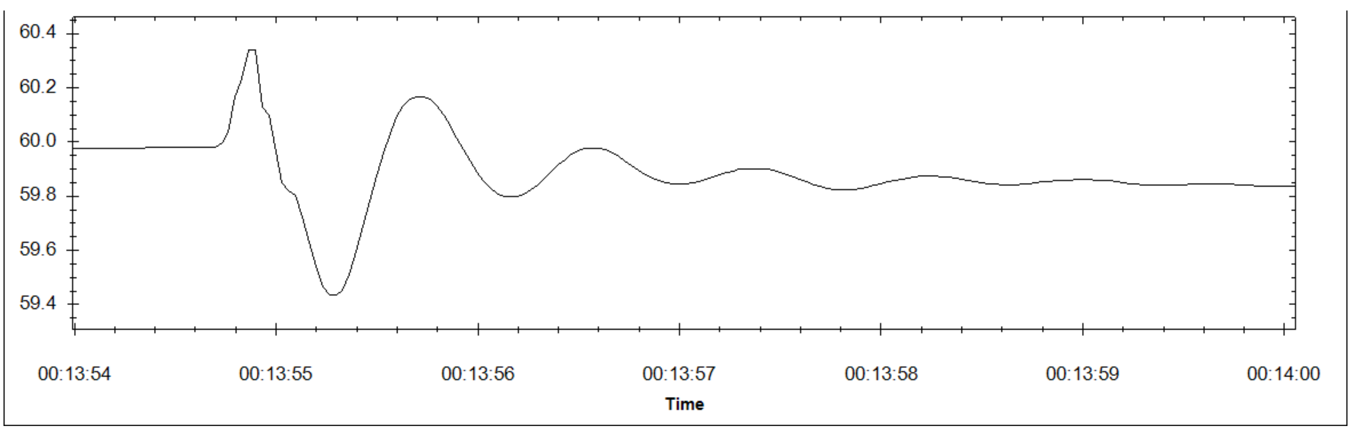

Figure F.2: Strong Response from a Montana local mode. Frequency signal Plotted

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures F.3–F.5.**

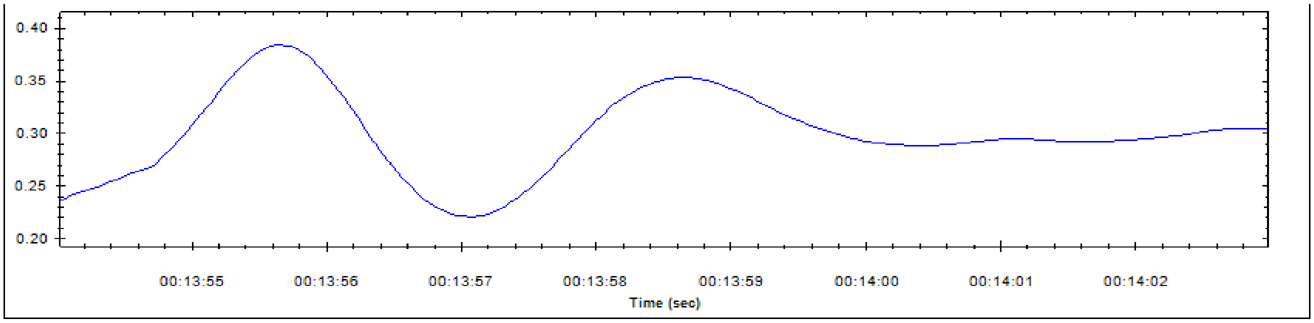

Figure F.3: Alberta Area Phase Angle with Respect to Center Point

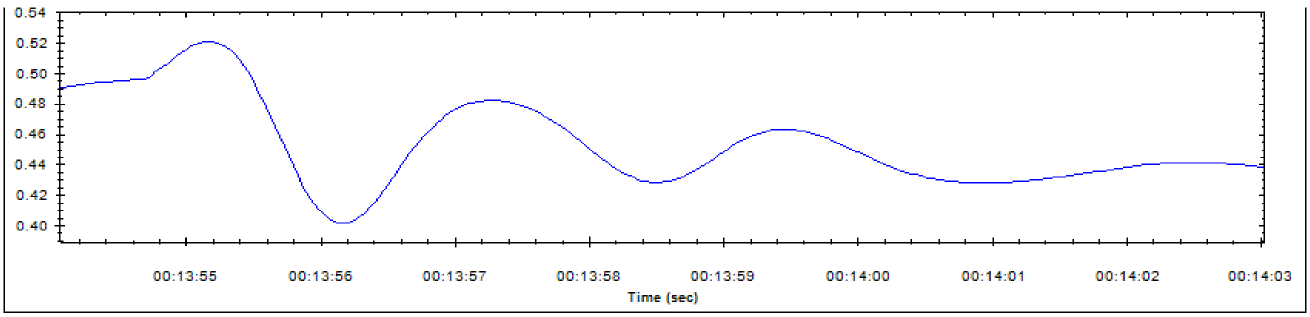

Figure F.4: British Columbia Area Phase Angle with Respect to Center Point

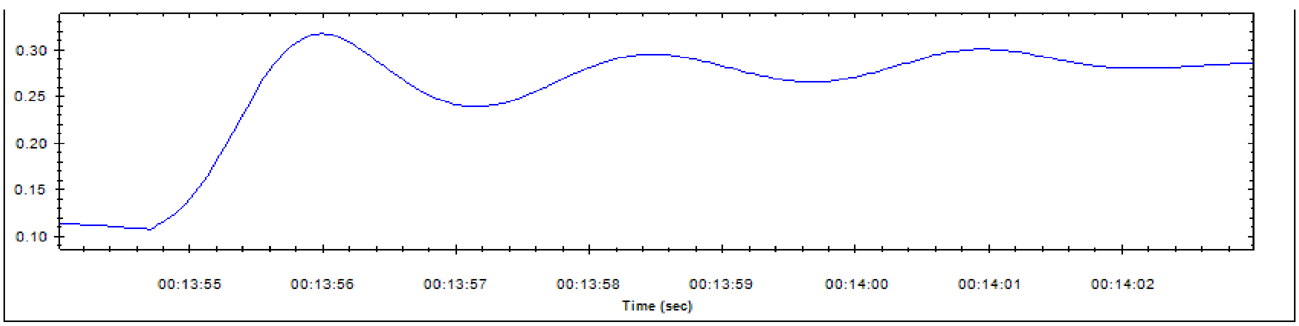

Figure F.5: Arizona Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus frequency signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:13:56 to 00:14:04 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:13:53. The analysis window is demonstrated in **Figure F.6**.

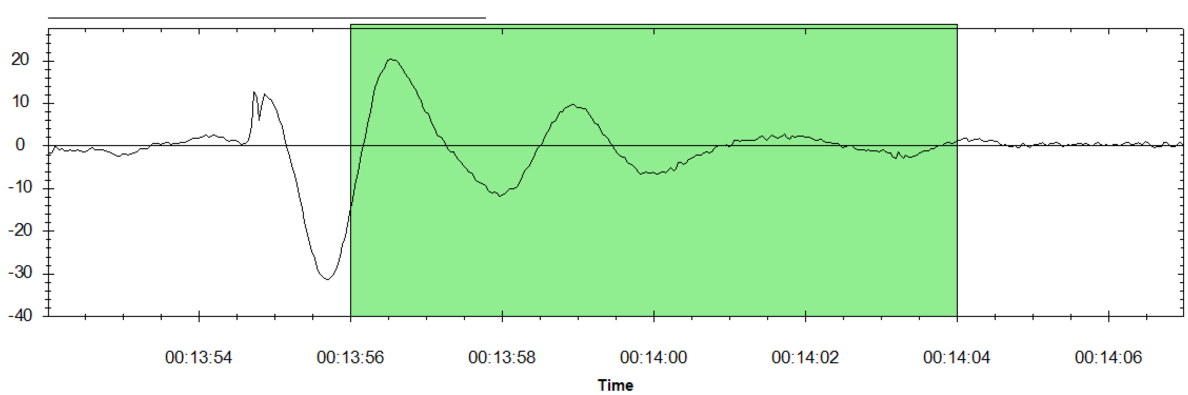

Figure F.6: Ringdown Analysis Window from 00:13:56 to 00:14:04

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. Figures F.7–F.9 demonstrate the signal match between the original and reconstructed signals.

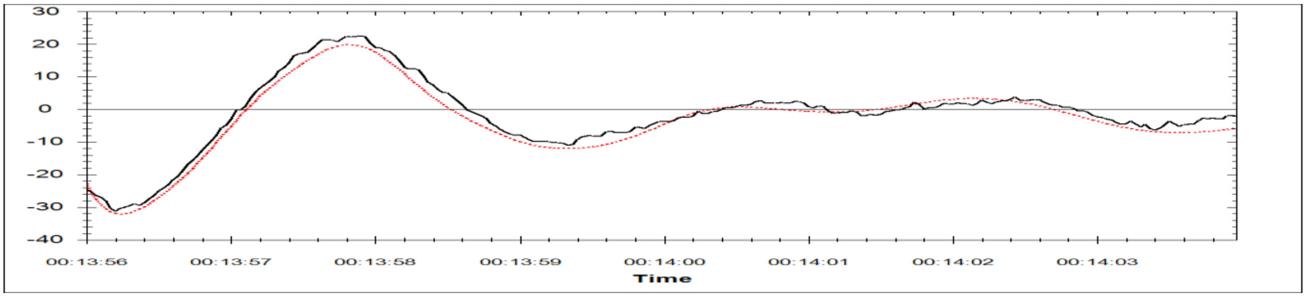

Figure F.7: Alberta Reconstructed and Original Signals

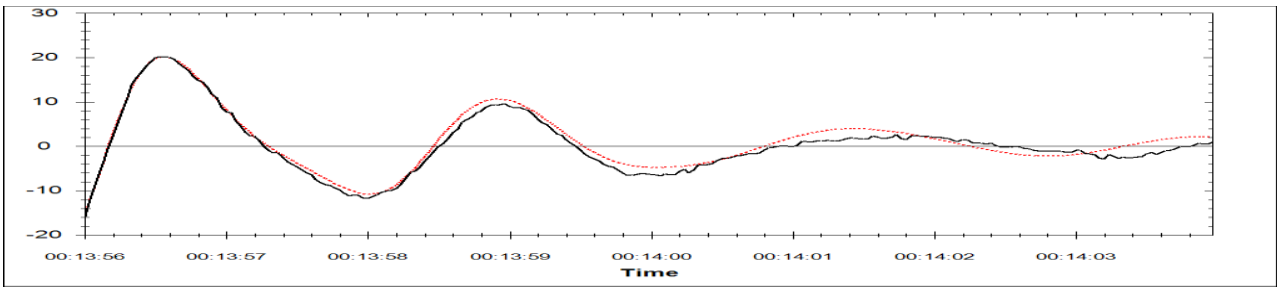

Figure F.8: British Columbia Reconstructed and Original Signals

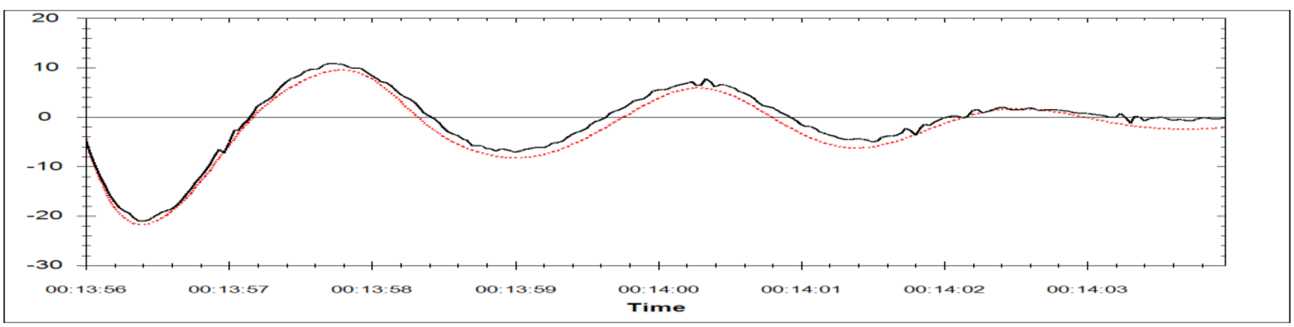

Figure F.9: Arizona Reconstructed and Original Signals

Table F.1 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 128 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the ERA analysis was 240 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[12]

Table F.1: Dominant Modes

Frequency (Hz)	Damping (%)	Total Energy (%)
0.42	12	51
1.29	8	31

[12] Frequency Disturbance Report

The mode shapes for the listed mode in **Table F.1** can be found in **Figures F.10** and **F.11**. The 0.42 Hz mode is defined between the Canadian West Coast regions and the southern portions of the Mountain and Pacific West United States Census Regions. A very strong participation factor is identified in the far north of the Canadian West Coast region for this mode shape. The 1.29 Hz mode here is a localized mode found only in the state of Montana and is not indicative of an interarea mode shape. However, it had such high energy in this event that it propagated as if it were an interarea mode.

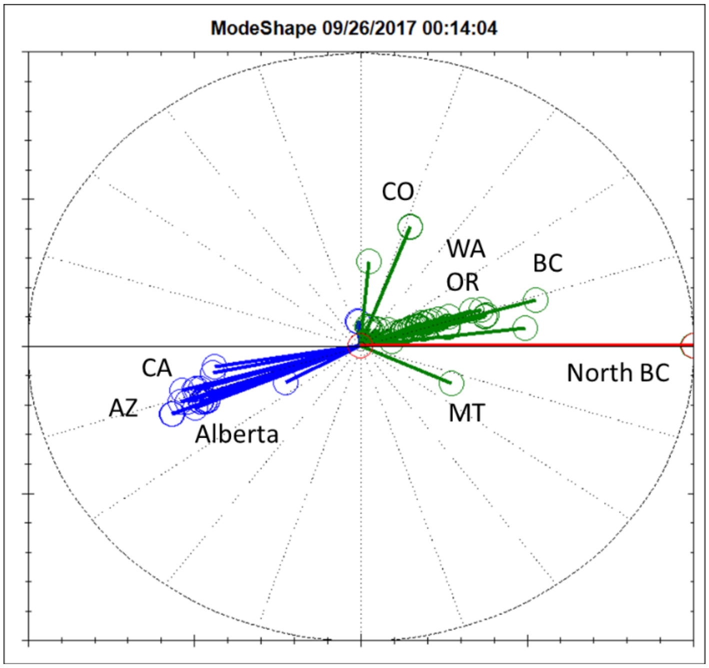

Figure F.10: Mode Shape for 0.42 Hz Mode

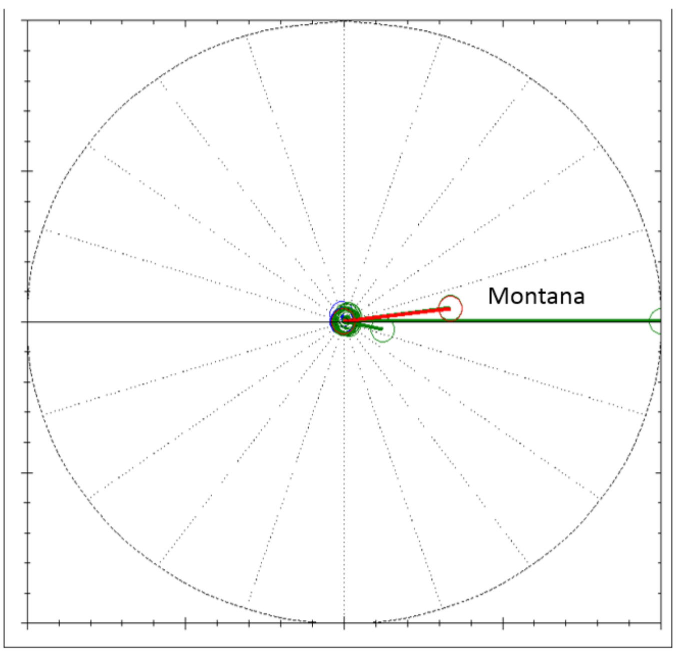

Figure F.11: Mode Shape for 1.29 Hz Mode

Event 2: 2016-01-27 00:19:25 UTC

This event involved a resource loss estimated at 620 MW tripping off-line. The system frequency response is shown in **Figure F.12**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

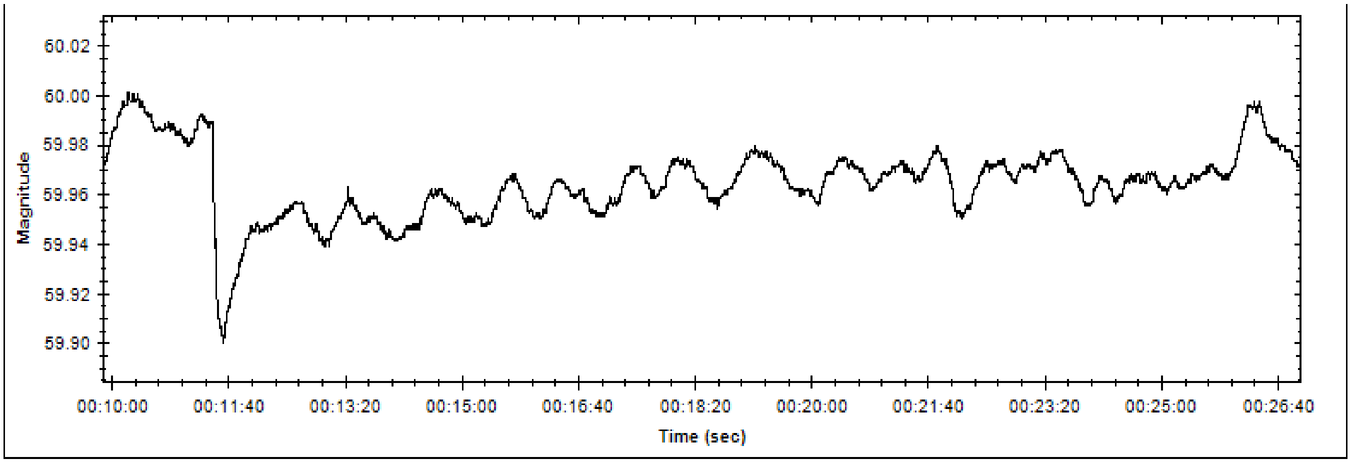

Figure F.12: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures F.13–F.15**

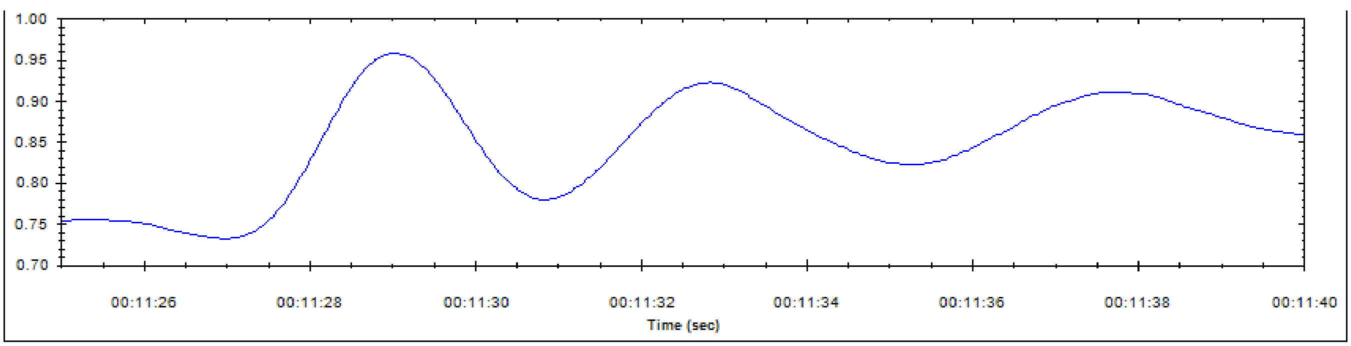

Figure F.13: Alberta Area Phase Angle with Respect to Center Point

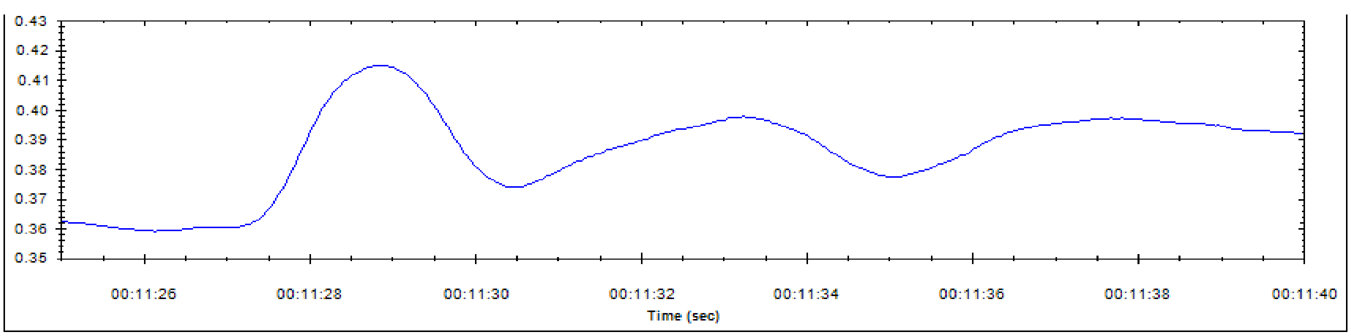

Figure F.14: British Columbia Area Phase Angle with Respect to Center Point

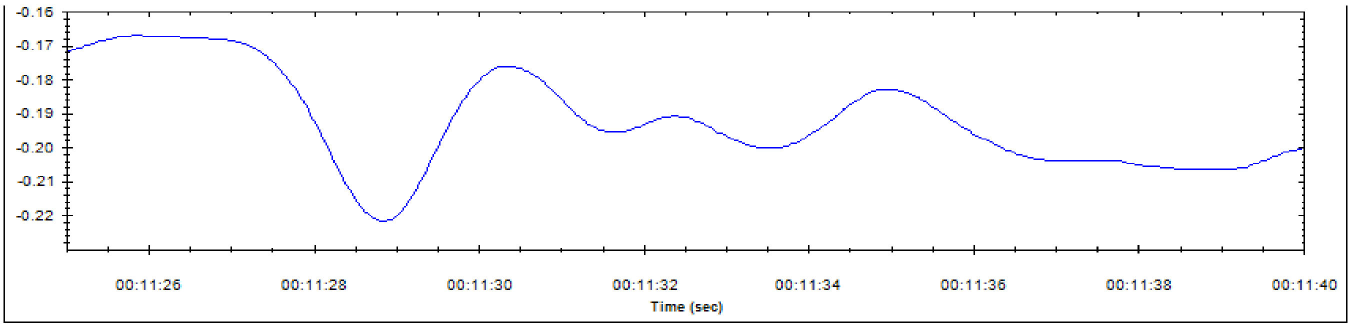

Figure F.15: Arizona Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus frequencies provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:11:28 to 00:11:37 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:11:25. The analysis window is demonstrated in **Figure F.16**.

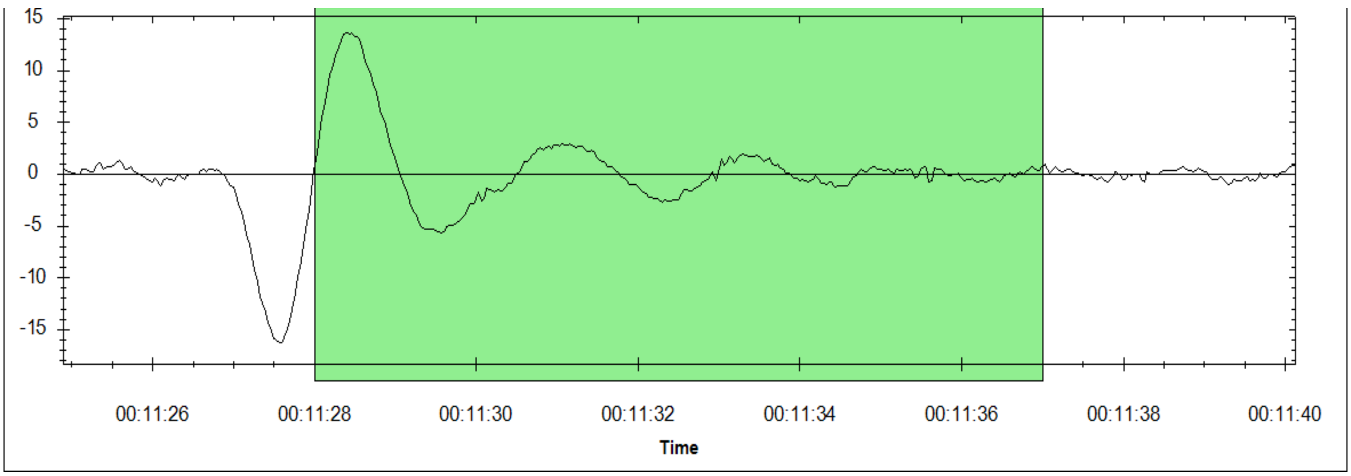

Figure F.16: Ringdown Analysis Window from 00:11:28 to 00:11:37

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures F.17– F.19** demonstrate the signal match between the original and reconstructed signal.

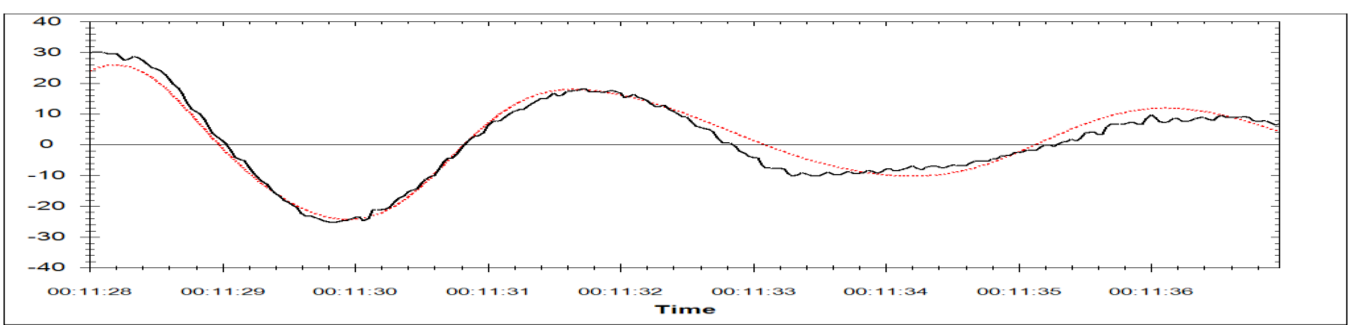

Figure F.17: Alberta Reconstructed and Original Signals

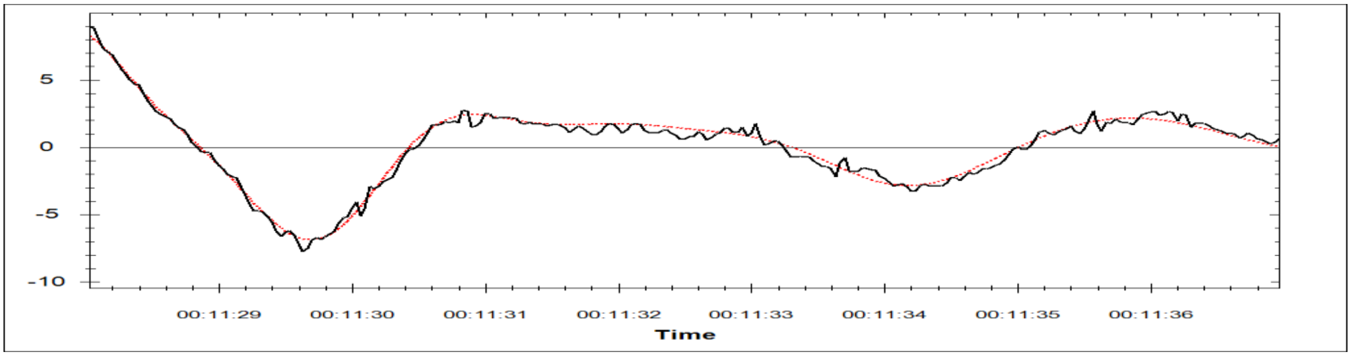

Figure F.18: British Columbia Reconstructed and Original Signals

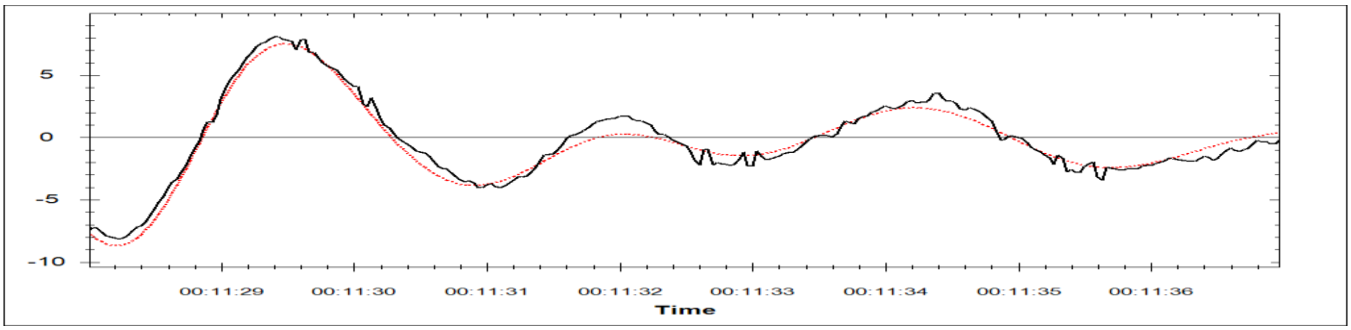

Figure F.19: Arizona Reconstructed and Original Signals

Table F.2 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 140 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the ERA analysis was 298 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[13]

Table F.2: Dominant Modes		
Frequency (Hz)	**Damping (%)**	**Total Energy (%)**
0.41	9.9	59
0.24	8.6	35

The mode shapes for the listed mode in **Table F.2** can be found in **Figures F.21** and **F.22**. The 0.42 Hz mode is defined between the Canadian West coast regions and the southern portions of the Mountain and Pacific West United States Census Regions. A very strong participation factor is identified in the far north of the Canadian West coast region for this mode shape.

[13] Frequency Disturbance Report

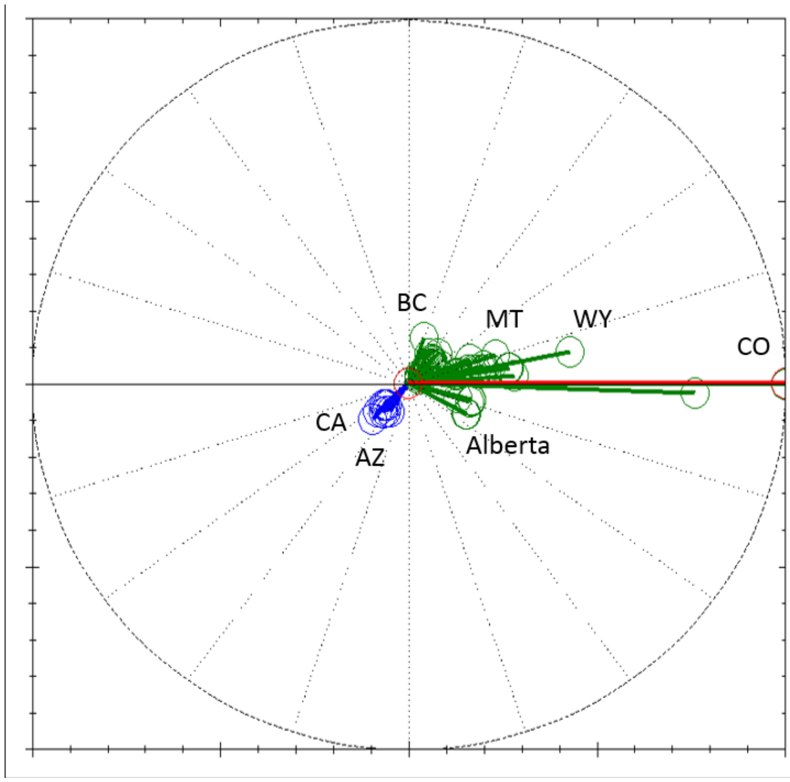

Figure F.21: Mode shape for 0.42 Hz Mode

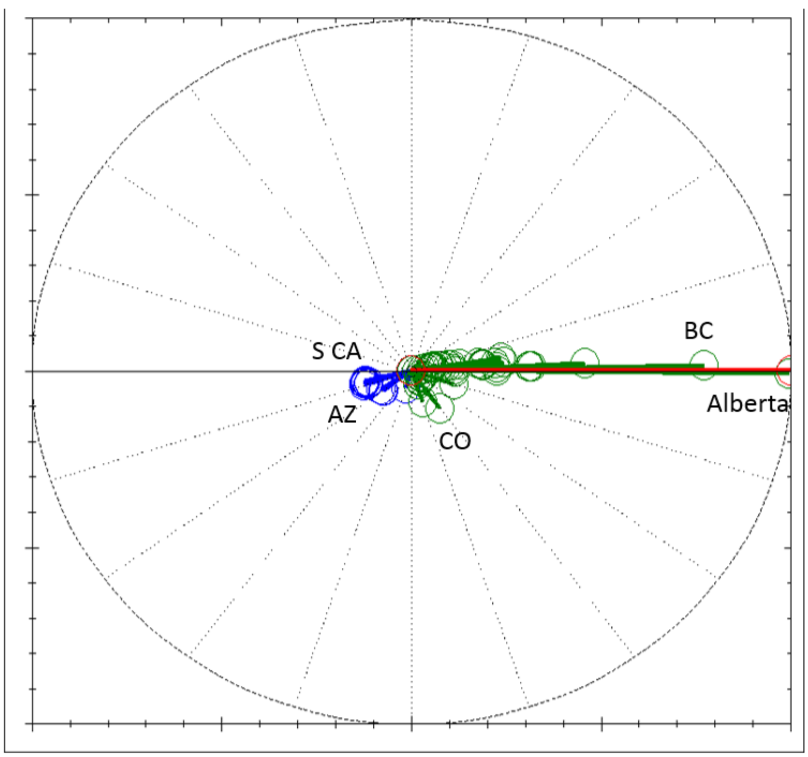

Figure F.22: Mode shape for 0.24 Hz Mode

Event 3: 2016-09-08 04:31:58 UTC

This event involved a resource loss estimated at 960 MW tripping off-line. The system frequency response is shown in Figure F.23. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small “sizzle” in frequency is normal for continuous fluctuations in generation and load.

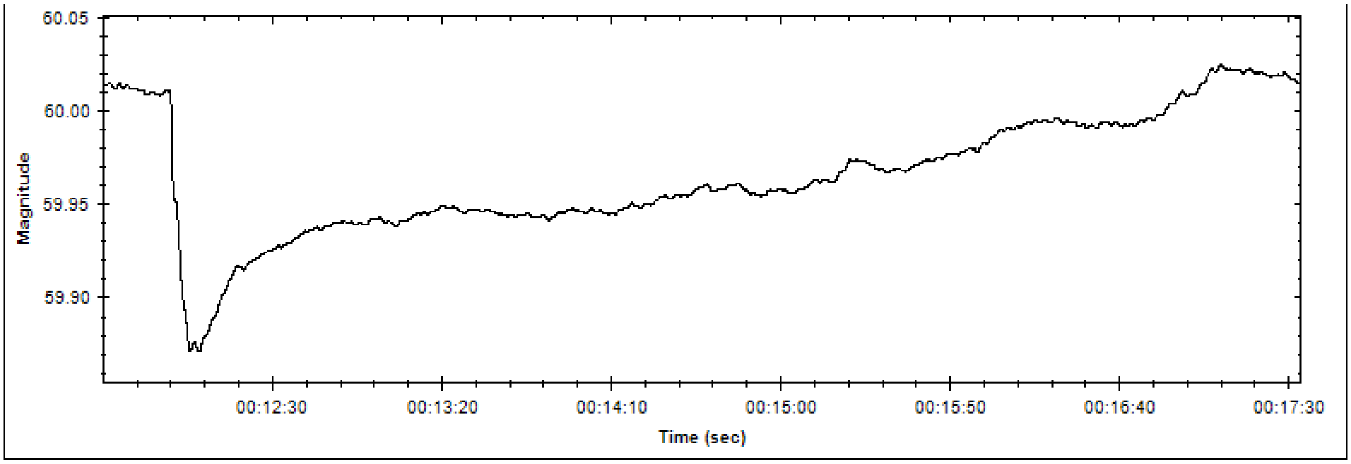

Figure F.23: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in Figures F.24–F.26.

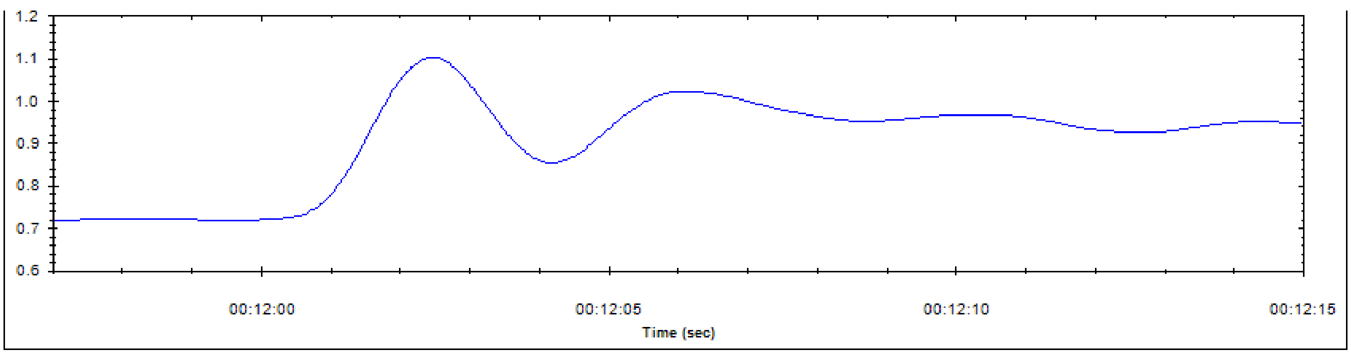

Figure F.24: Alberta Area Phase Angle with Respect to Center Point

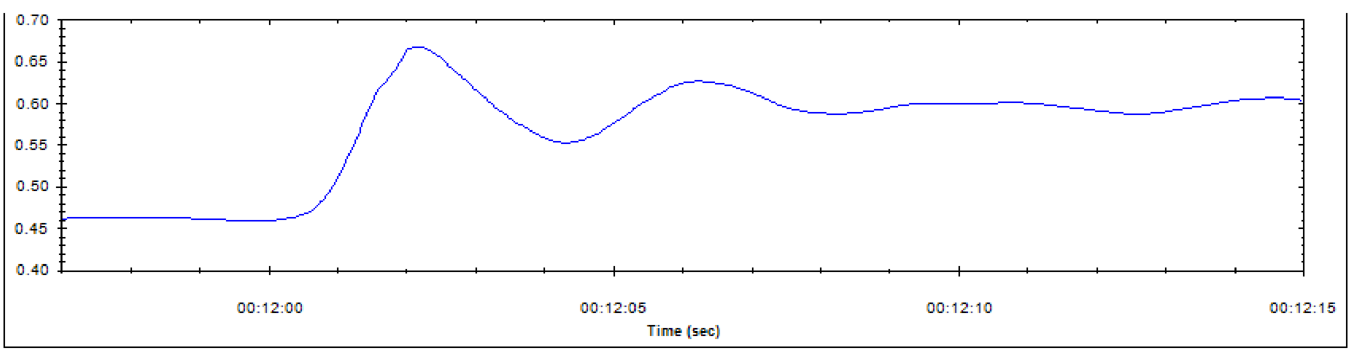

Figure F.25: British Columbia Area Phase Angle with Respect to Center Point

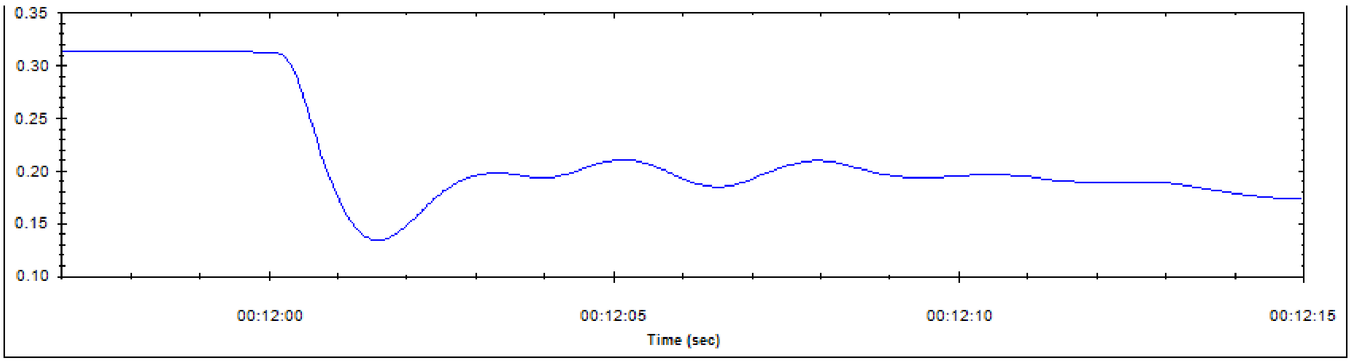

Figure F.26: Southern California Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus frequencies provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:12:04 to 00:12:13 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:11:58. The analysis window is demonstrated in **Figure F.27.**

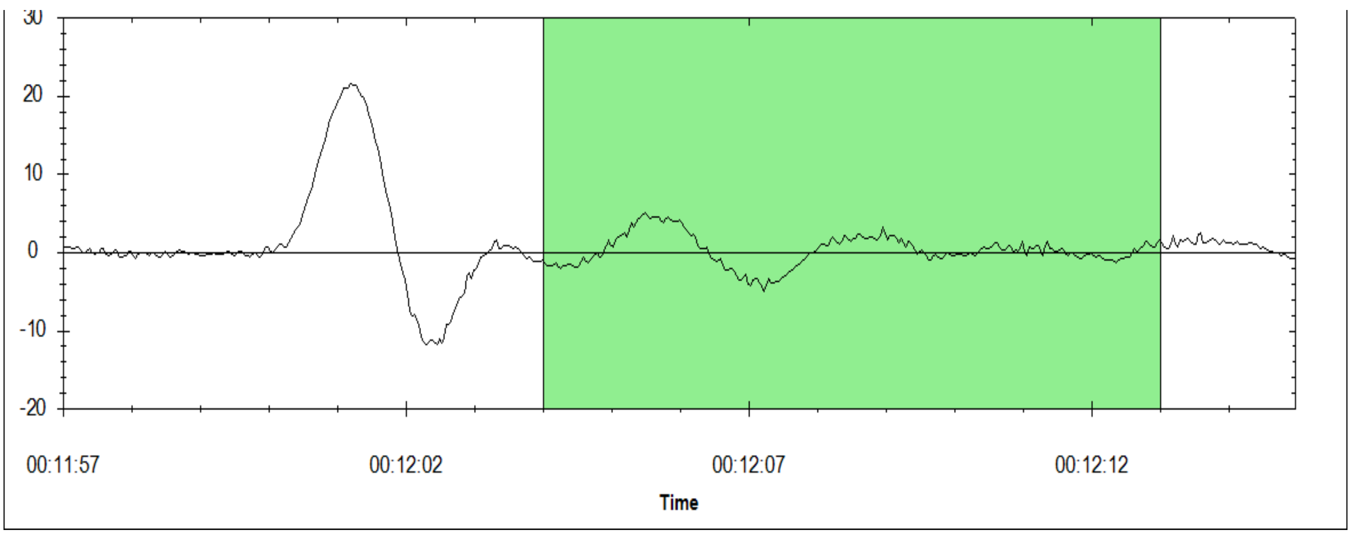

Figure F.27: Ringdown Analysis Window from 00:12:04 to 00:12:13

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures F.28**–**F.30** demonstrate the signal match between the original and reconstructed signals.

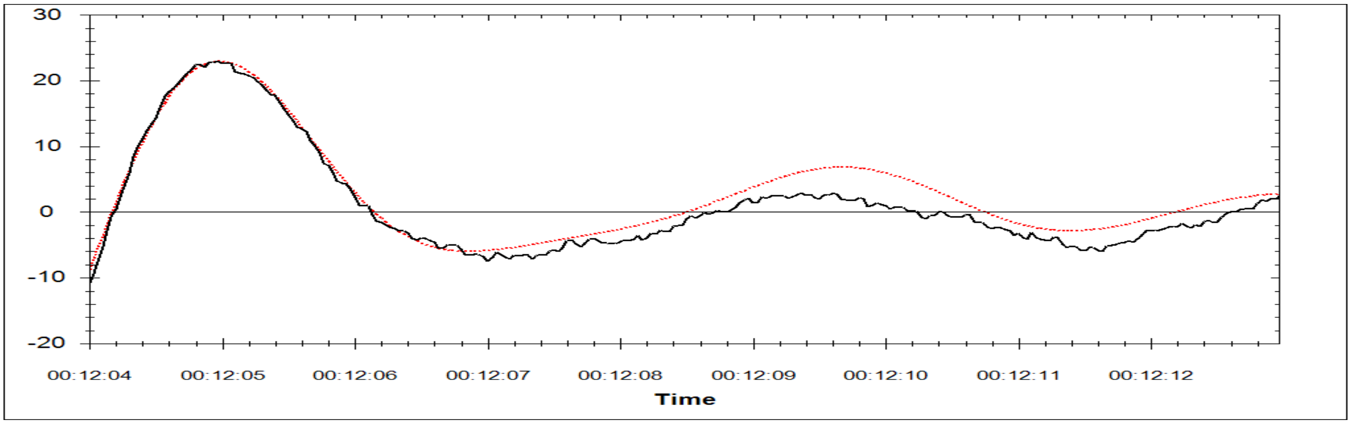

Figure F.28: Alberta Reconstructed and Original Signals

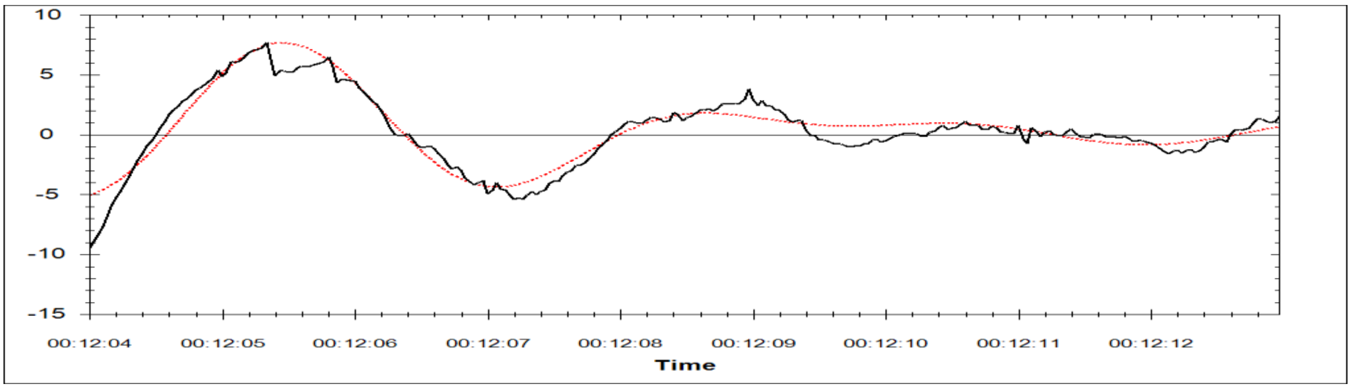

Figure F.29: British Columbia Reconstructed and Original Signals

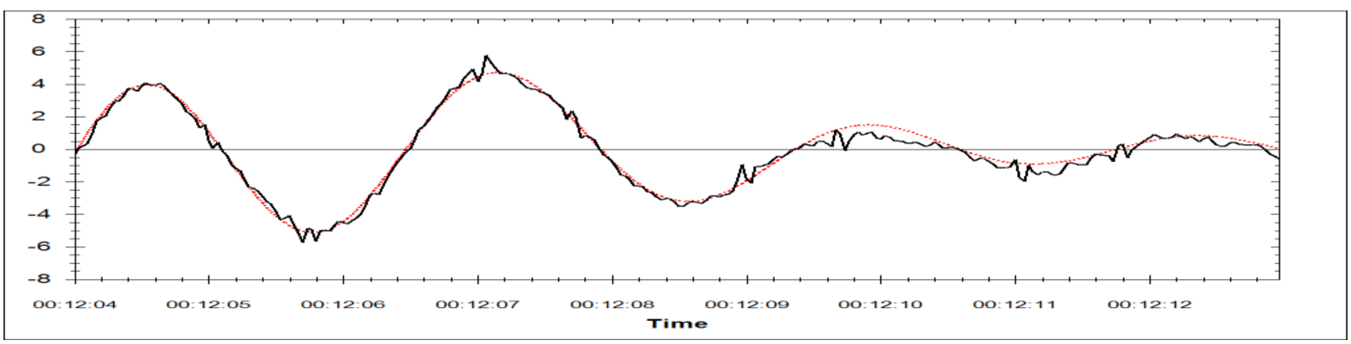

Figure F.30: Arizona Reconstructed and Original Signals

Table F.3 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 181 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the ERA analysis was 577 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[14]

Table F.3: Dominant Modes

Frequency (Hz)	Damping (%)	Total Energy (%)
0.24	18.4	70
0.38	10.2	30

[14] Frequency Disturbance Report

The mode shapes for the listed mode in **Table F.3** can be found in **Figures F.31** and **F.32**. The 0.24 Hz mode shape has the same mode shape as identified in Event 2, which spans the Canadian West Pacific region to the southern West Pacific United States census region. The 0.38 Hz mode has a more complex mode shape that spans between the same two regions; however, the middle West Mountain United States census region has a high participation factor in that mode shape.

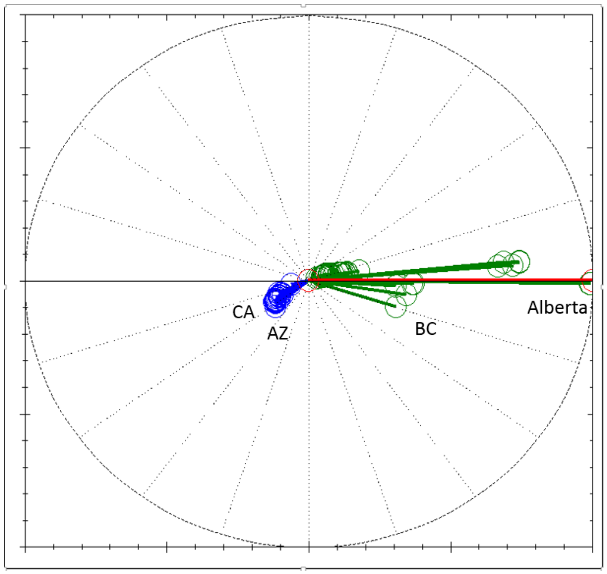

Figure F.31: Mode shape for 0.24 Hz Mode

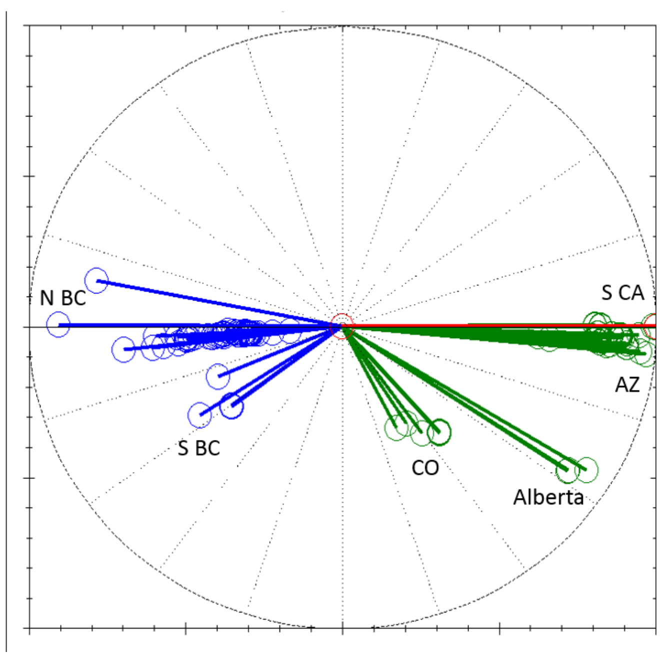

Figure F.32: Mode shape for 0.38 Hz Mode

Event 4: 2016-09-21 20:26:37 UTC

This event involved a resource loss estimated at 960 MW tripping off-line. The system frequency response is shown in **Figure F.33**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

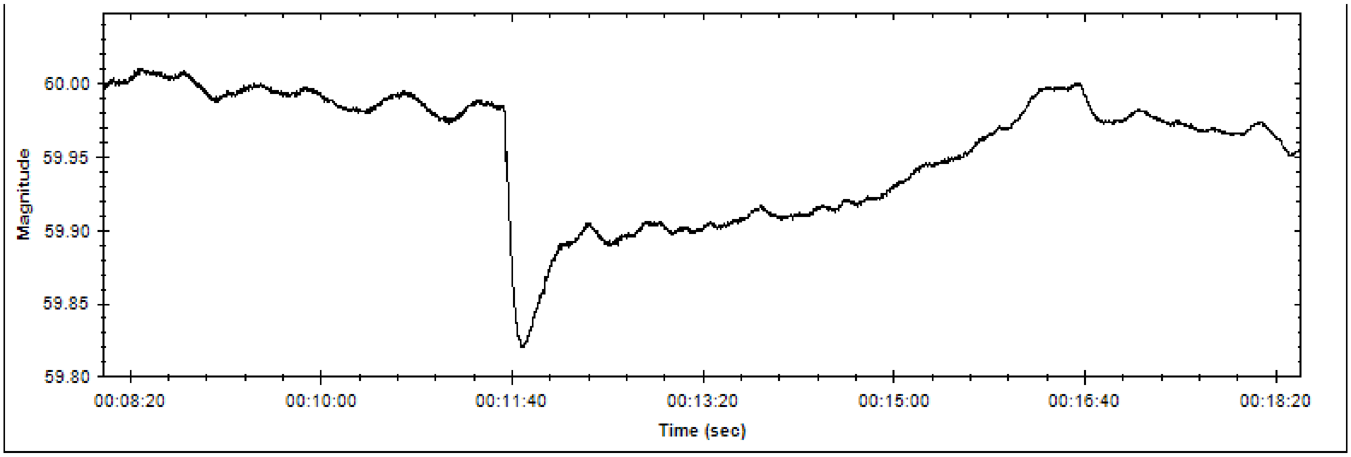

Figure F.33: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures F.34–F.36.**

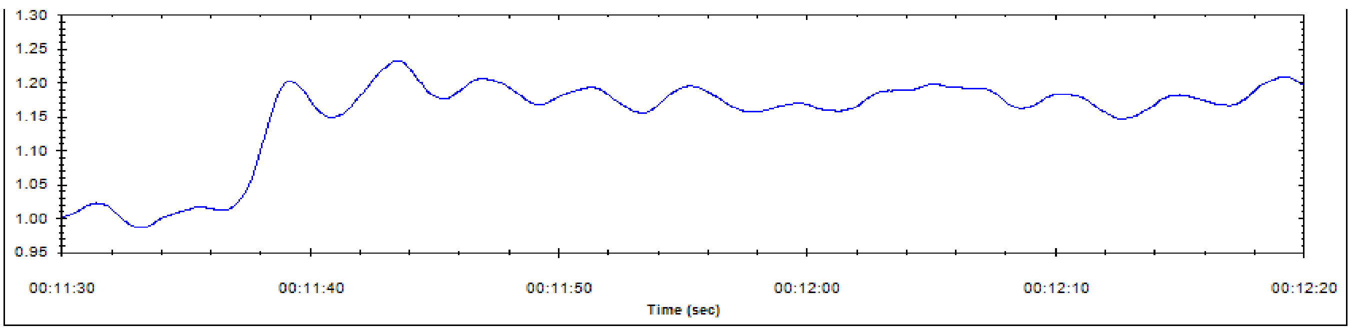

Figure F.34: Alberta Area Phase Angle with Respect to Center Point

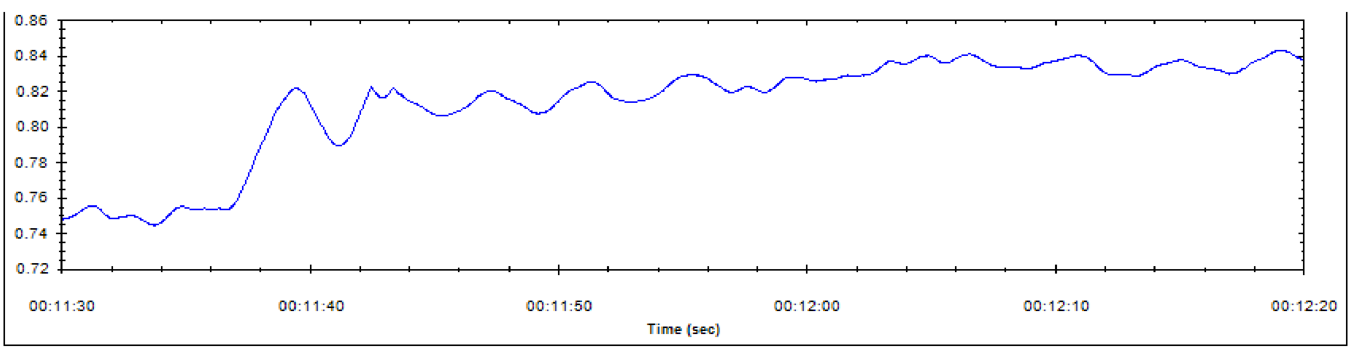

Figure F.35: British Columbia Area Phase Angle with Respect to Center Point

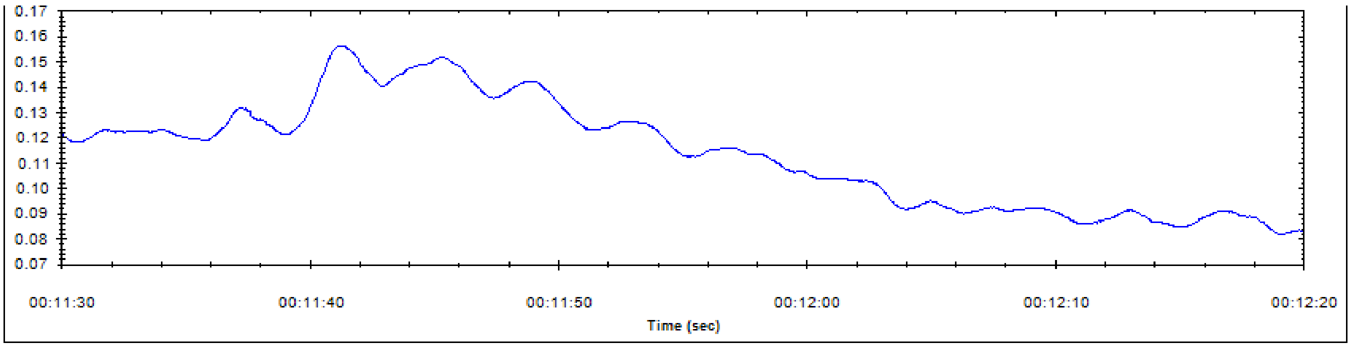

Figure F.36: Arizona Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the first derivative of the voltage phase angle signals provided by the RCs relative to a center point. The analyzers chose an analysis window from time stamp 00:11:40 to 00:11:49 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:11:38. The analysis window is demonstrated in **Figure F.37.**

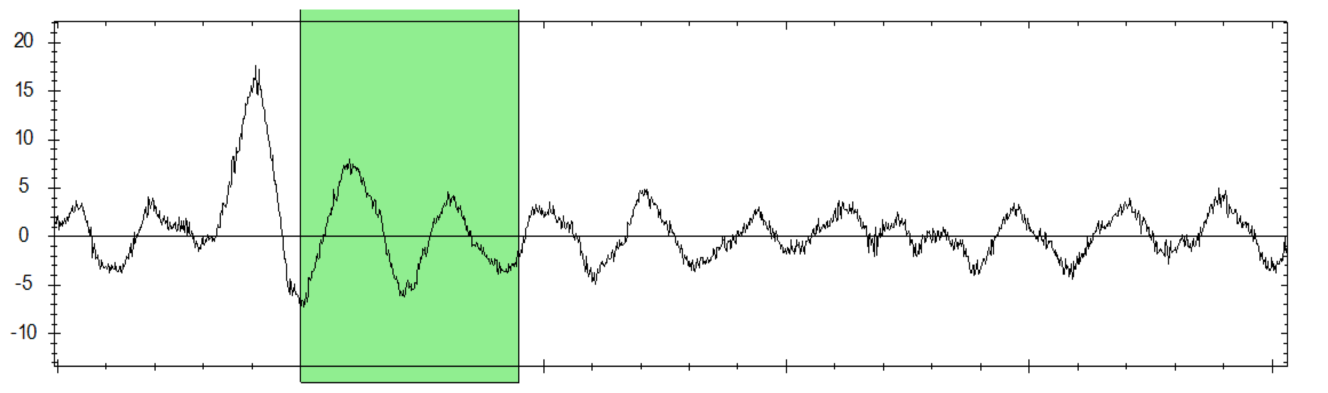

Figure F.37: Ringdown Analysis Window from 00:11:40 to 00:11:49

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures F.38–F.41** demonstrate the signal match between the original and reconstructed signal.

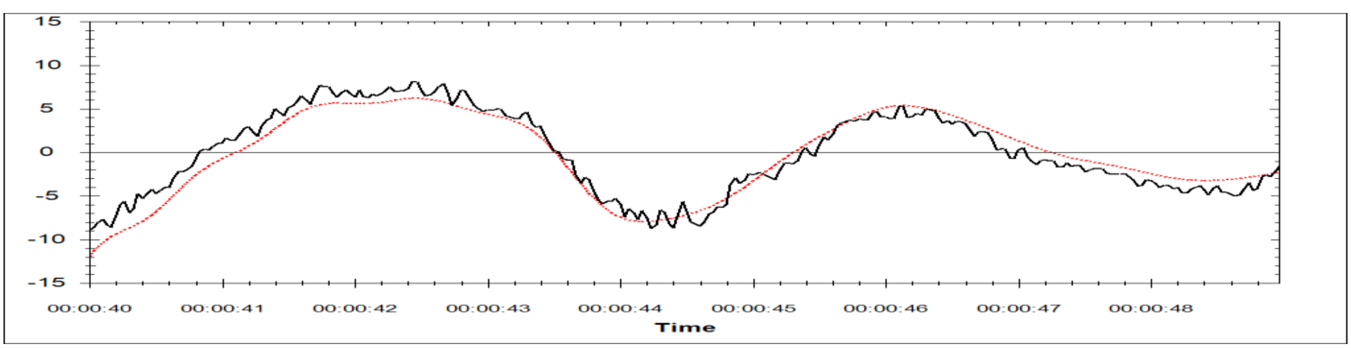

Figure F.38: Alberta Reconstructed and Original Signals

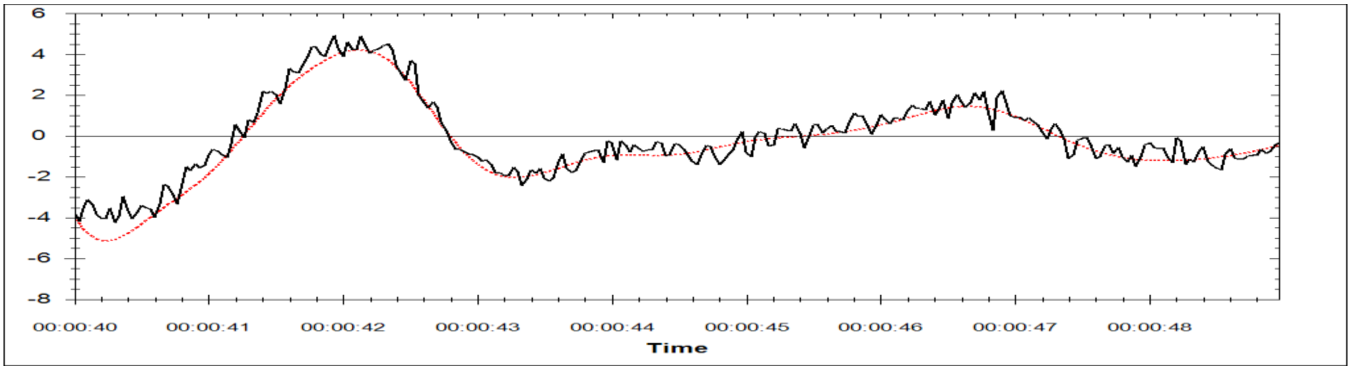

Figure F.39: British Columbia Reconstructed and Original Signals

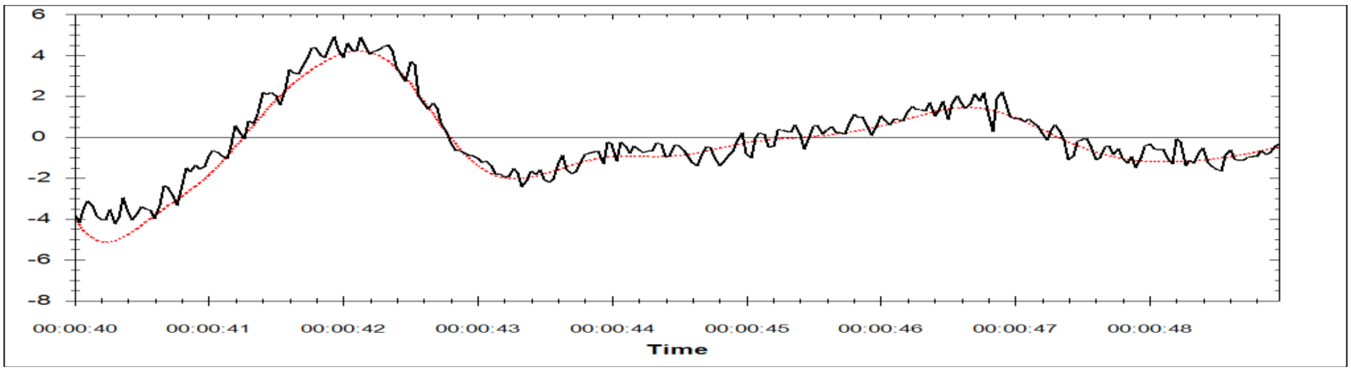

Figure F.40: Arizona Reconstructed and Original Signals

Table F.4 provides the summary of the Prony results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 208 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the Prony analysis was 1220 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[15]

Table F.4: Dominant Modes

Frequency (Hz)	Damping (%)	Total Energy (%)
0.24	9.84	56
0.40	10.77	29

The mode shapes for the listed mode in **Table F.4** can be found in **Figures F.41** and **F.42**. The 0.24 Hz mode shape is the previously defined North to South mode in previous WECC studies. The 0.40 Hz mode shape, however, demonstrates a more complex mode shape that has regions in the Central Mountain, South Pacific, and Canadian providence sections of the Western Interconnection.

[15] Frequency Disturbance Report

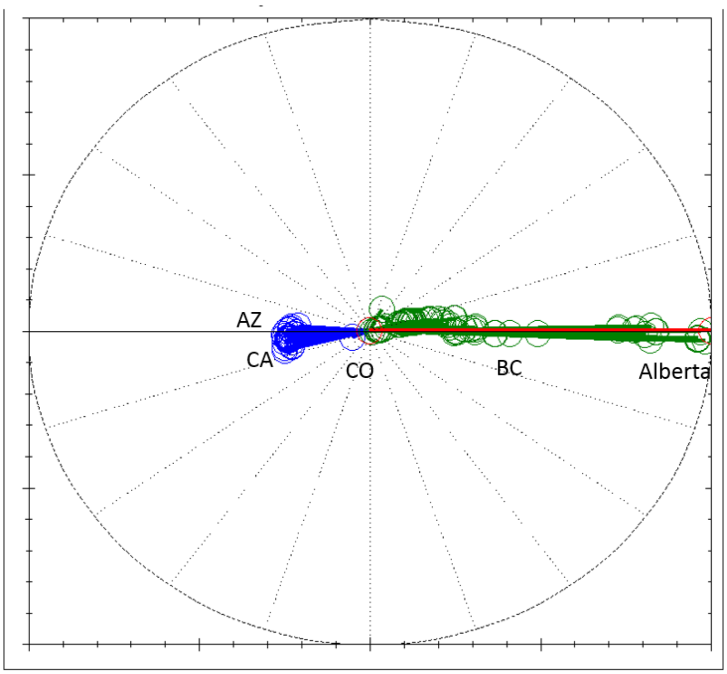

Figure F.41: Mode Shape for 0.24 Hz Mode

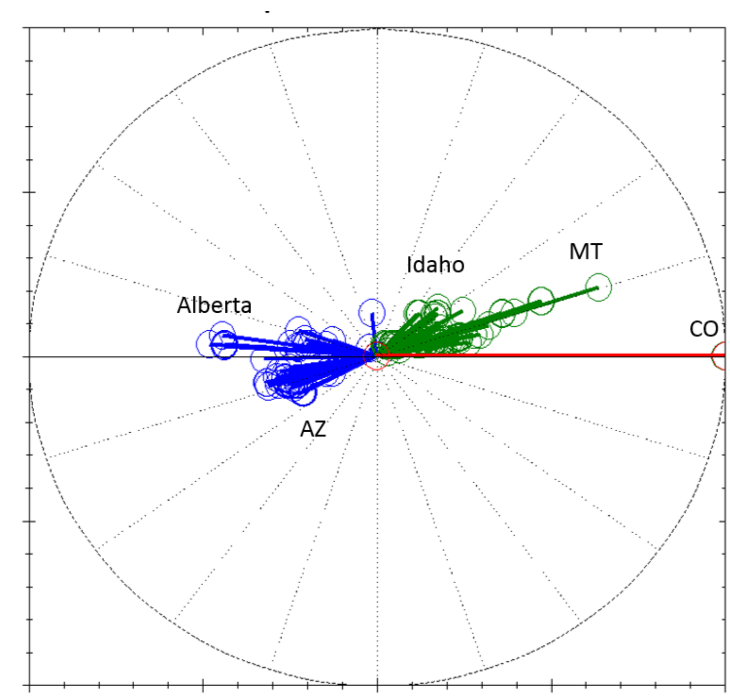

Figure F.42: Mode Shape for 0.40 Hz Mode

Event 5: 2017-01-20 08:01:05 UTC

This event involved a resource loss estimated at 930 MW tripping off-line. The system frequency response is shown in **Figure F.43**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

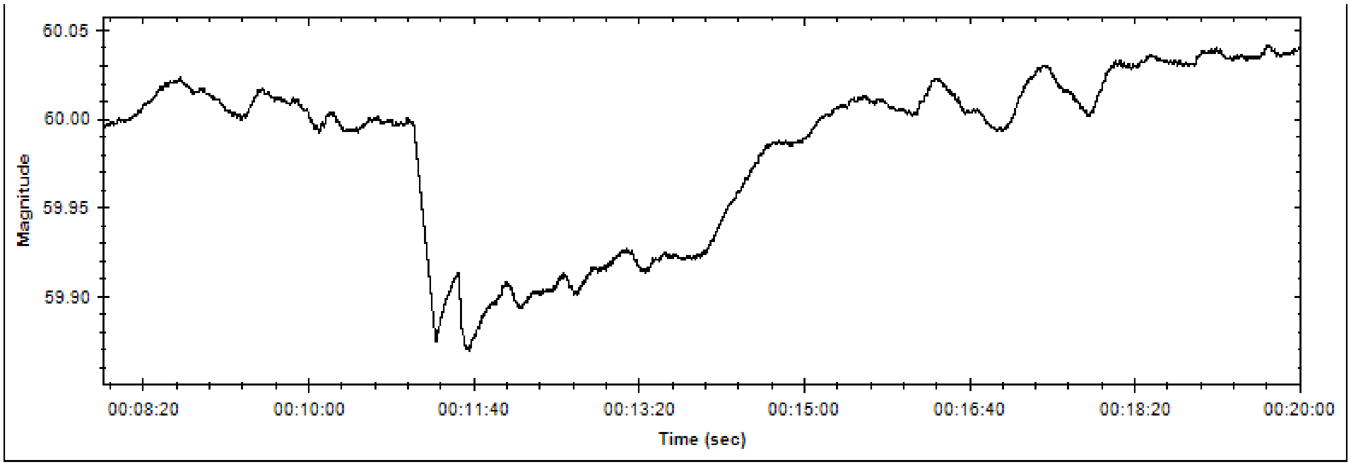

Figure F.43: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures F.44**–**Figure F.46.**

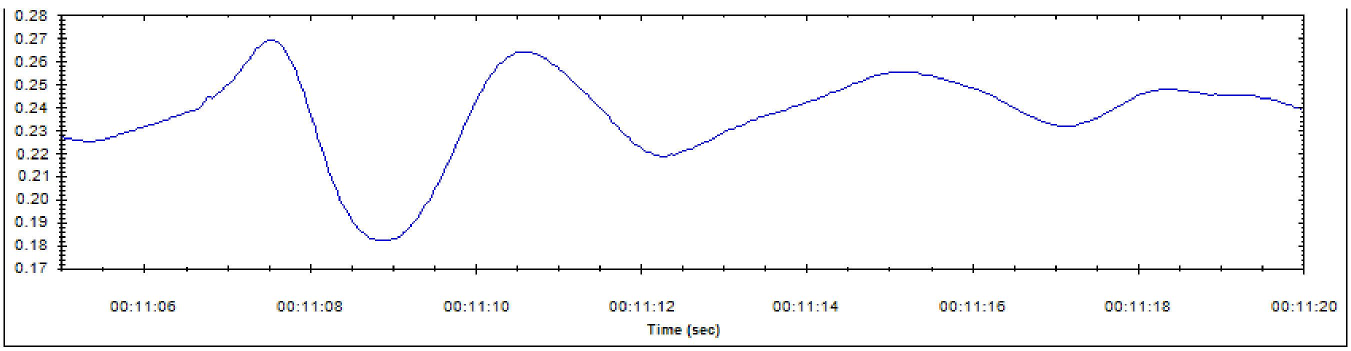

Figure F.44: Alberta Area Phase Angle with Respect to Center Point

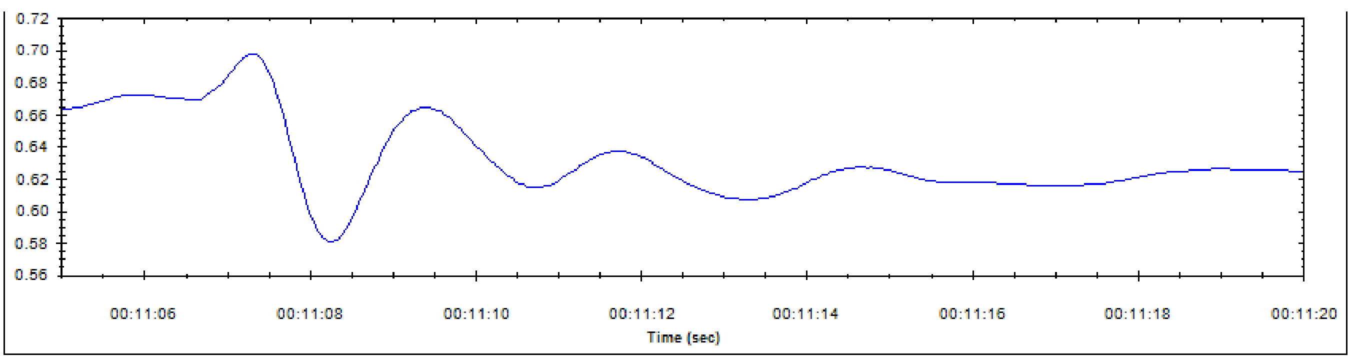

Figure F.45: British Columbia Area Phase Angle with Respect to Center Point

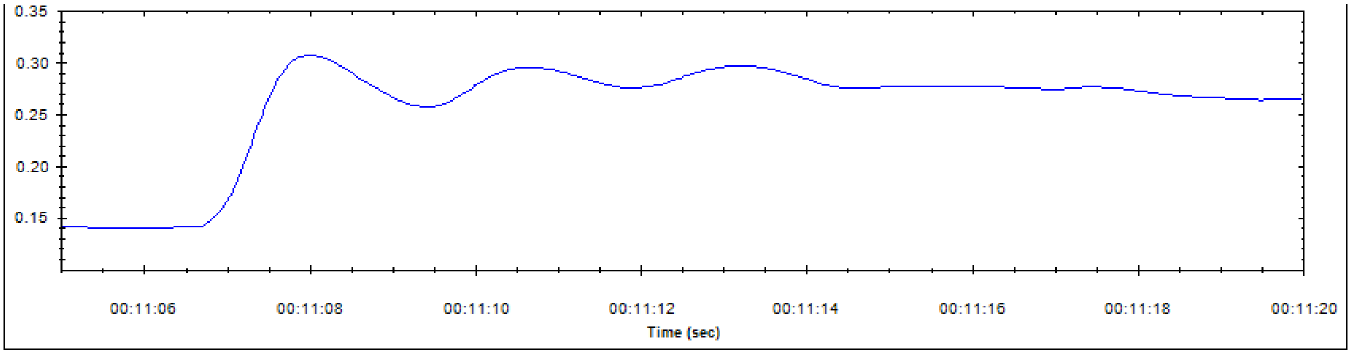

Figure F.46: Arizona Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus frequency signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:11:44 to 00:11:52 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:11:58. The analysis window is demonstrated in **Figure F.47**.

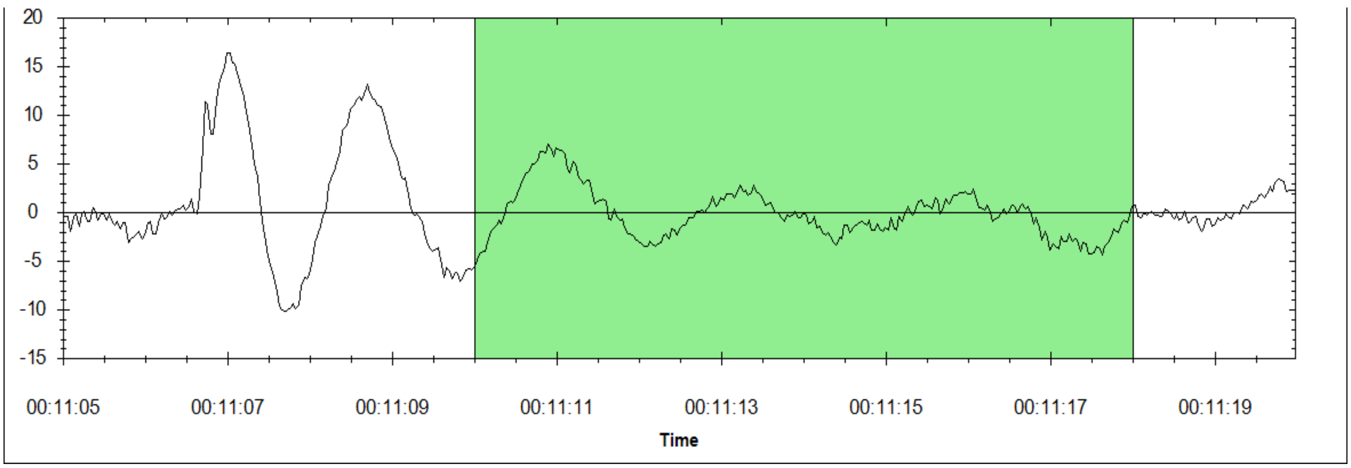

Figure F.47: Ringdown Analysis Window from 00:11:44 to 00:11:52

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. **Figures F.48**–**Figure F.50** demonstrate the signal match between the original and reconstructed signal.

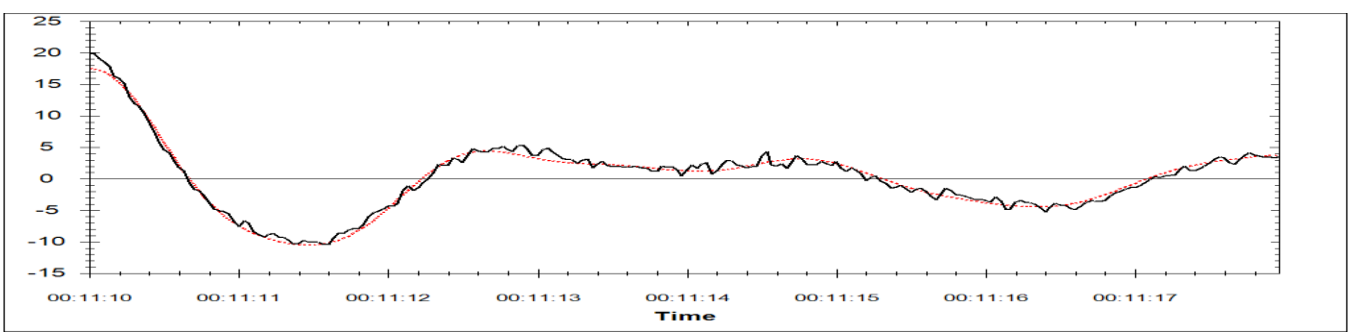

Figure F.48: Alberta Reconstructed and Original Signals

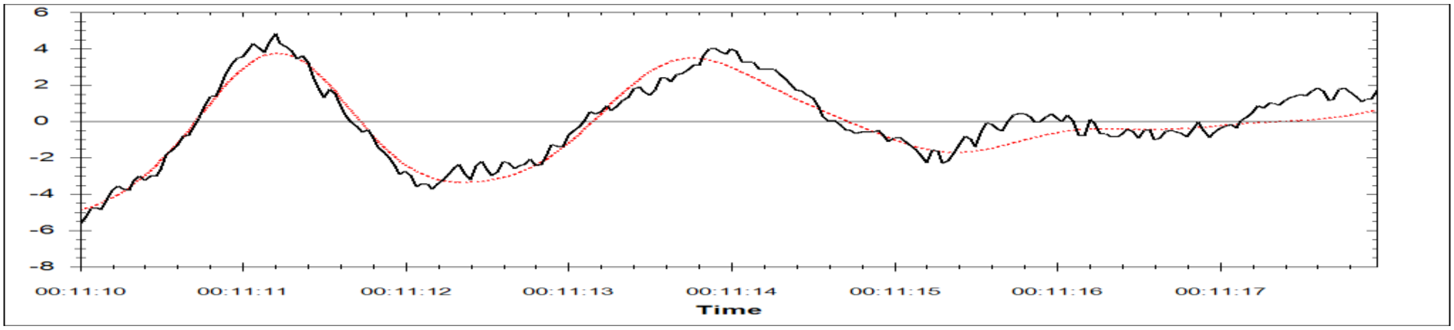

Figure F.49: British Columbia Reconstructed and Original Signals

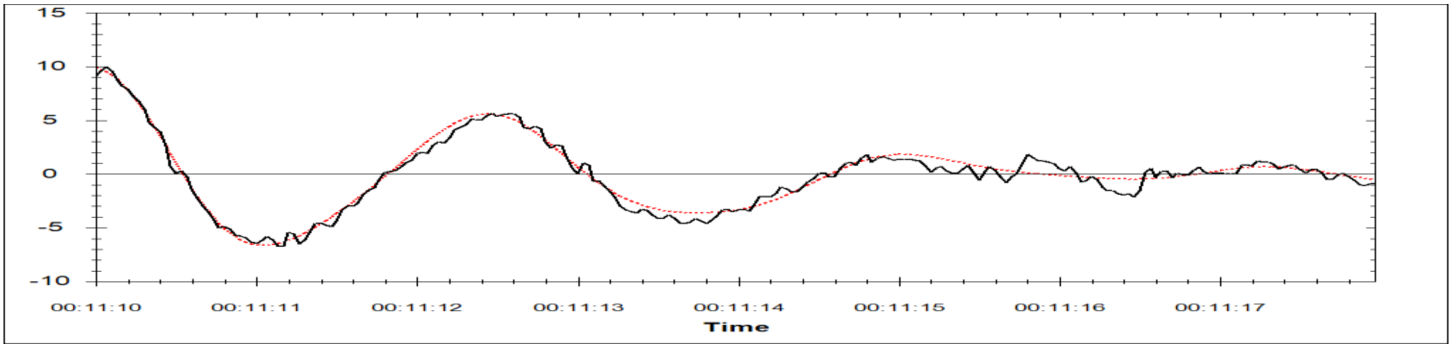

Figure F.50: Arizona Reconstructed and Original Signals

Table F.5 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 123 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the HTLS analysis was 542 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[16]

Table F.5: Dominant Modes		
Frequency (Hz)	**Damping (%)**	**Total Energy (%)**
0.39	13.8	90

The mode shapes for the listed mode in **Table F.5** can be found in **Figure F.51**. The 0.38 Hz mode has a more complex mode shape that spans between the northern Mountain and eastern West Canadian regions and the southern Pacific and Mountain regions. These regions support previous findings for NS Mode B in the WI.

[16] Frequency Disturbance Report

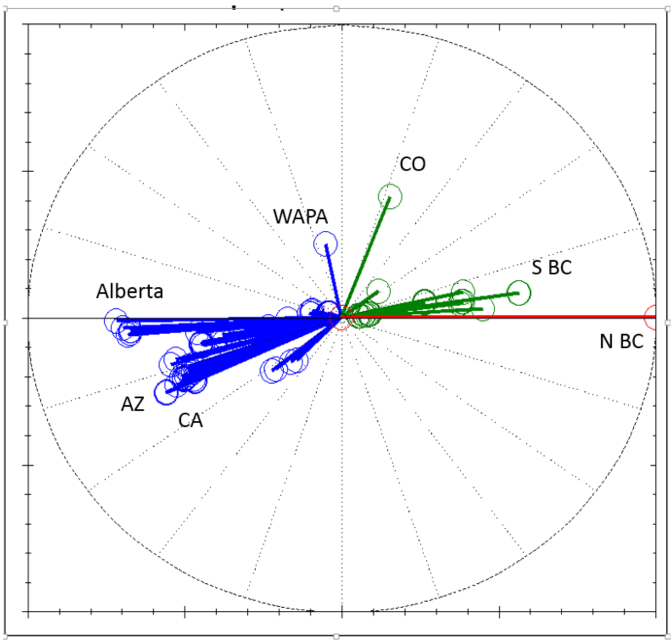

Figure F.51: Mode Shape for 0.39 Hz Mode

Event 6: 2017-03-09 03:07:06 UTC

This event involved a resource loss estimated at 930 MW tripping off-line. The system frequency response is shown in **Figure F.52**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

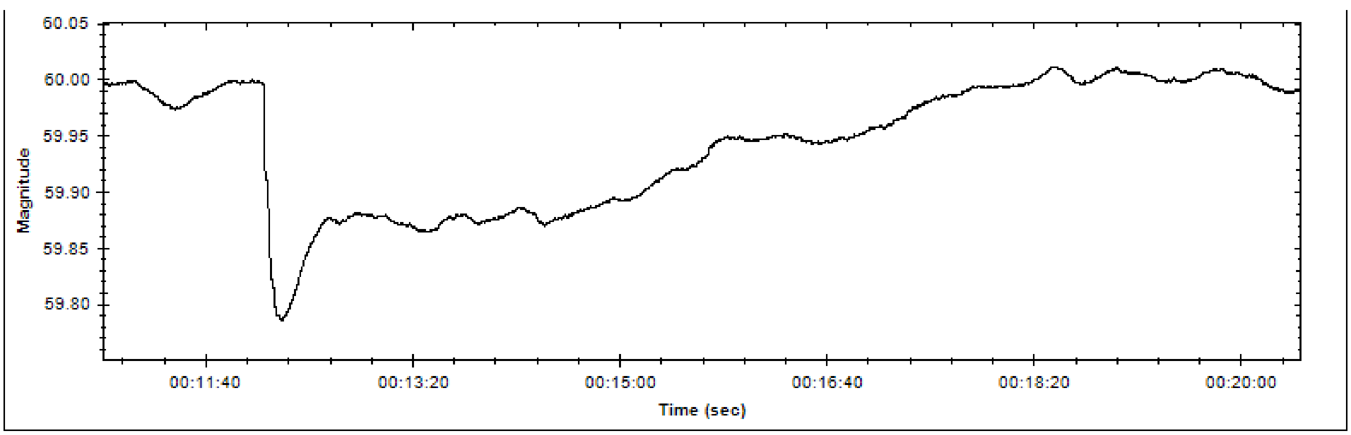

Figure F.52: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures F.53–F.55**.

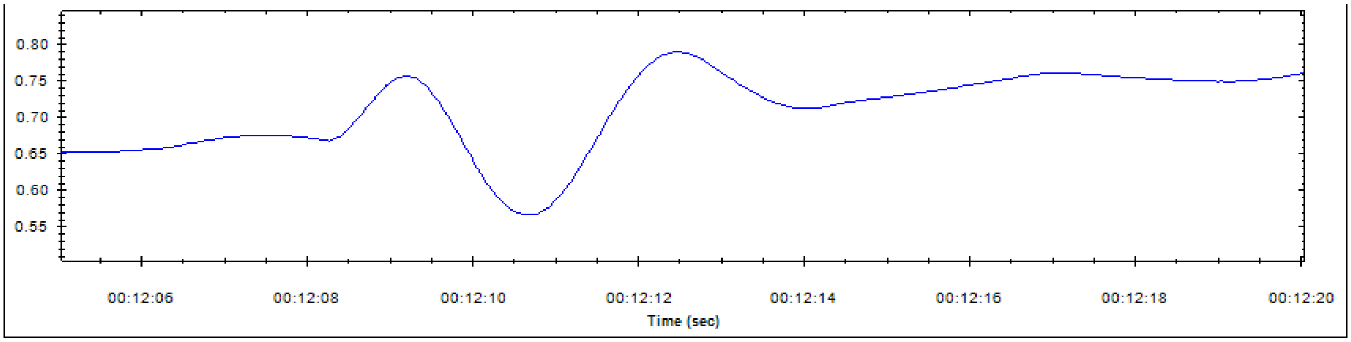

Figure F.53: Alberta Area Phase Angle with Respect to Center Point

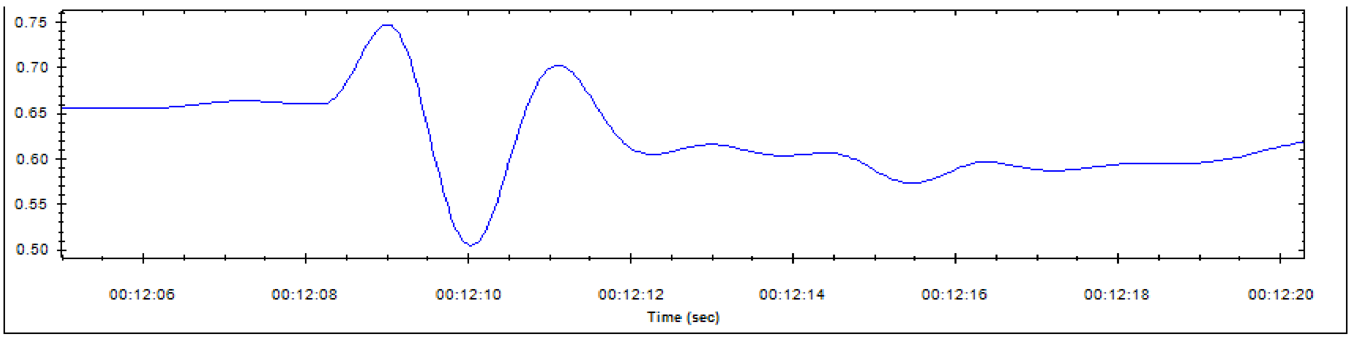

Figure F.54: British Columbia Area Phase Angle with Respect to Center Point

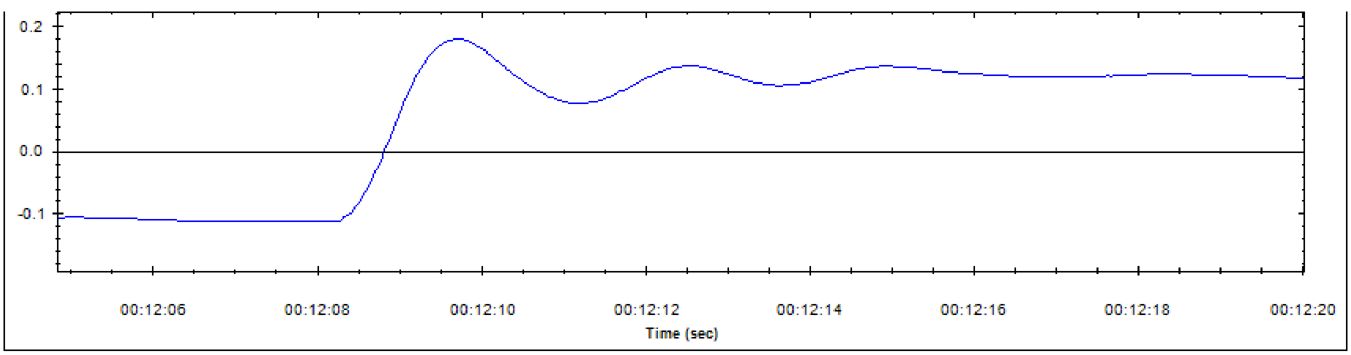

Figure F.55: Arizona Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus frequency signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:12:10 to 00:12:17 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:11:58. The analysis window is demonstrated in **Figure F.56.**

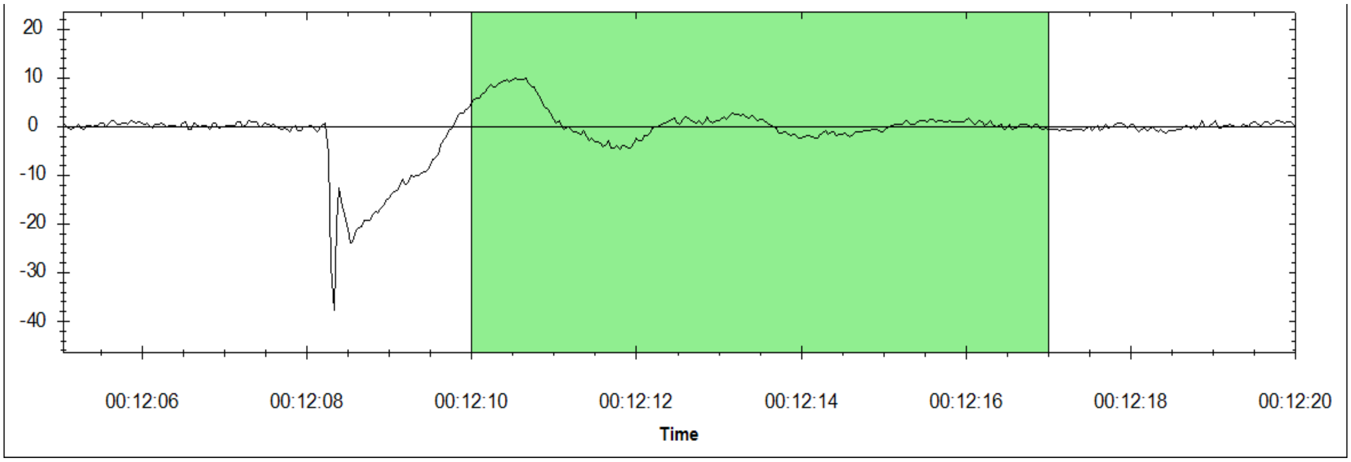

Figure F.56: Ringdown Analysis Window from 00:12:10 to 00:12:17

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. Figures F.57–F.59 demonstrate the signal match between the original and reconstructed signal.

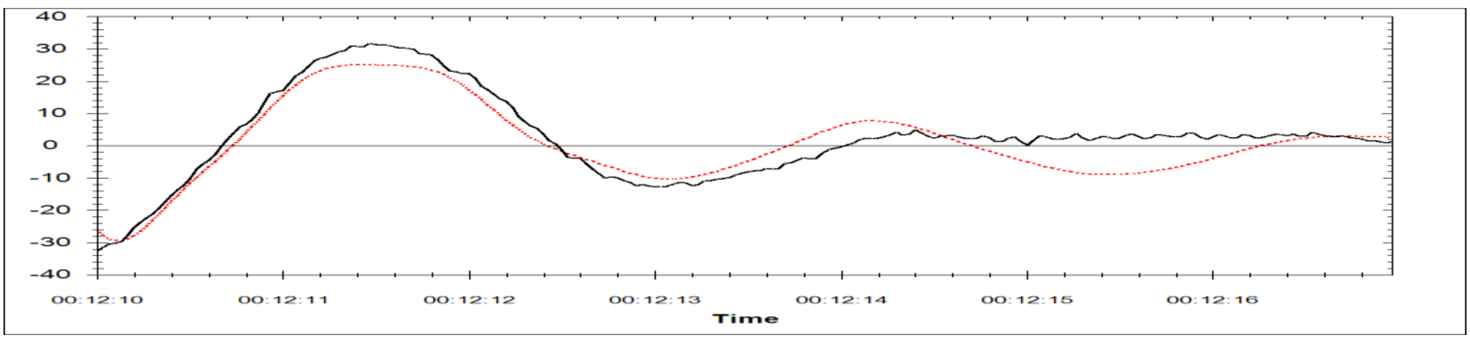

Figure F.57: Alberta Reconstructed and Original Signals

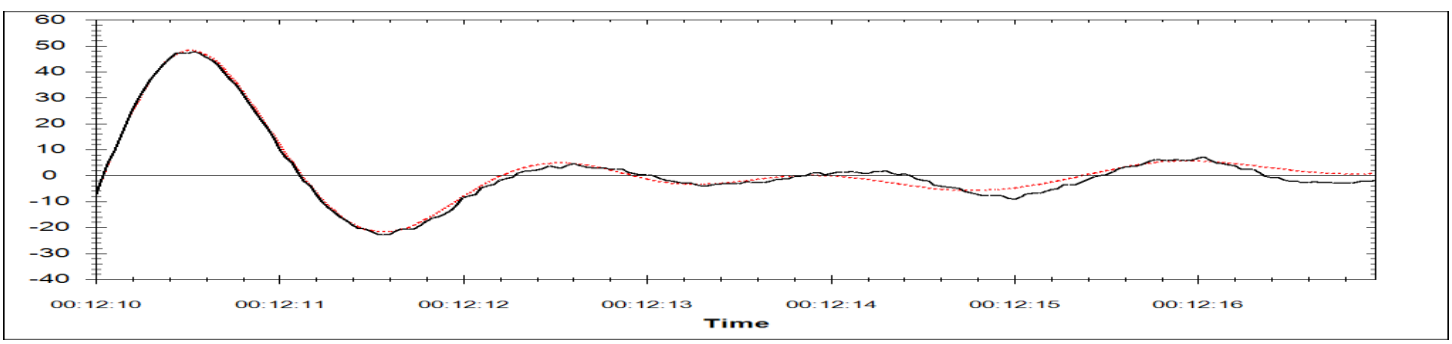

Figure F.58: British Columbia Reconstructed and Original Signals

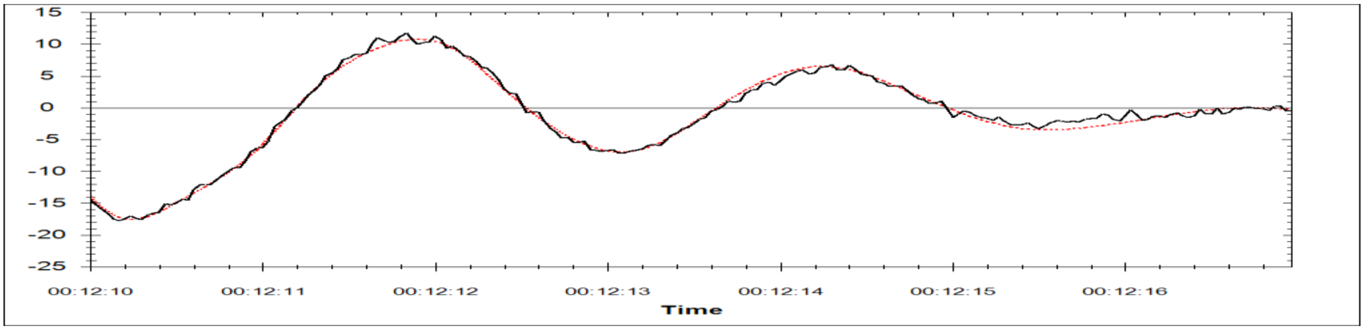

Figure F.59: Arizona Reconstructed and Original Signals

Table F.6 provides the summary of the Prony results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 86 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the Prony analysis was 146 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[17]

Table F.6: Dominant Modes		
Frequency (Hz)	**Damping (%)**	**Total Energy (%)**
0.39	14	71
0.55	14	20

The mode shapes for the listed mode in **Table F.6** can be found in **Figures F.60** and **F.61**. The 0.39 Hz mode shape conforms to the previously identified shape in Event 5; however, the shape is slightly distorted. The 0.55 Hz mode shape has participation factors in the Western Canadian providences to the North California area where the signal data was referenced to. This mode shape is more accurately described in the benchmarking section of the summary report.

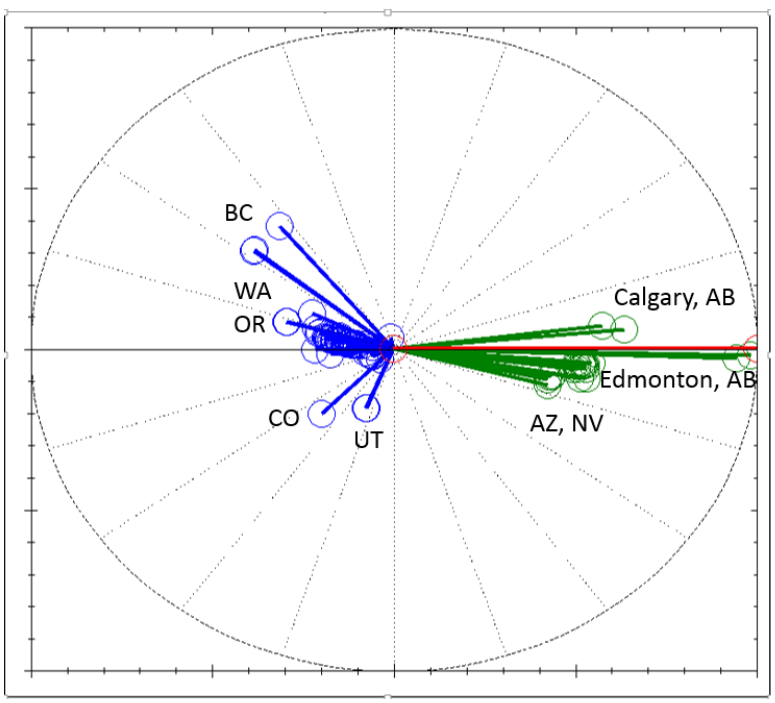

Figure F.60: Mode Shape for 0.39 Hz Mode

17 Frequency Disturbance Report

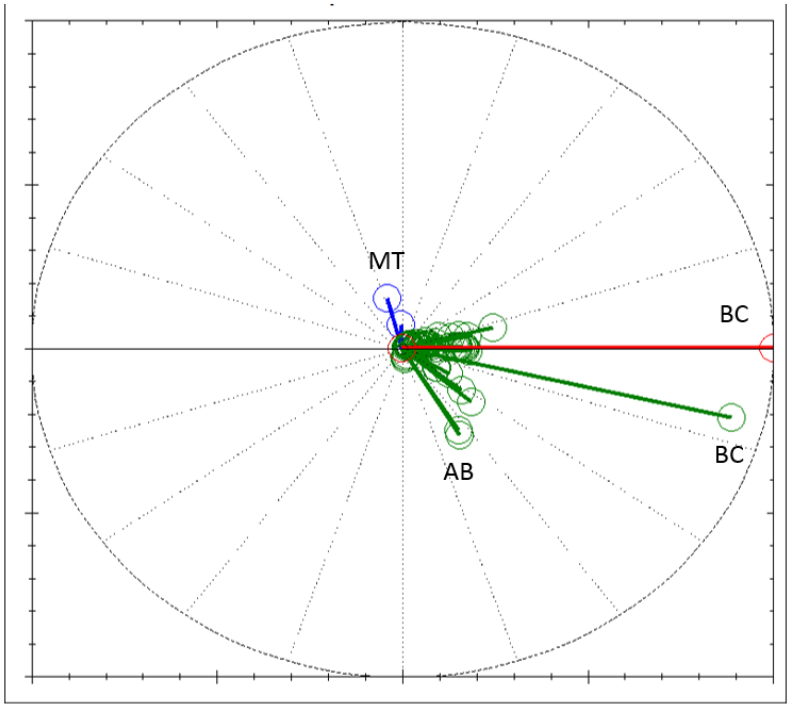

Figure F.61: Mode shape for 0.55 Hz Mode

Event 7: 2017-05-10 17:13:30 UTC

This event involved a resource loss estimated at 560 MW tripping off-line. The system frequency response is shown in **Figure F.62**. The oscillatory behavior immediately following the generation loss event was analyzed as an input to determine interarea modes. No forced oscillations were observed in this event; the small "sizzle" in frequency is normal for continuous fluctuations in generation and load.

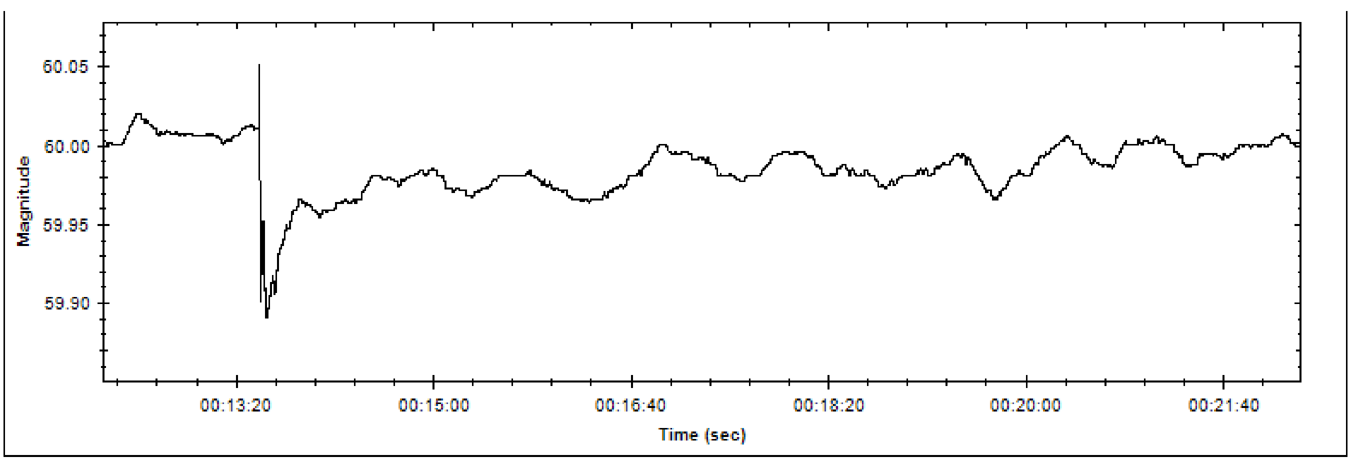

Figure F.62: PMU Frequency Measurement during Disturbance

The analysis done for this event entailed a detailed look into the phase angles with relation to a center point. This allowed the analyzers to geographically determine interarea modes as they relate to the generic geographical regions. The phase angle signals with relation to the center point are found in **Figures F.63–F.65.**

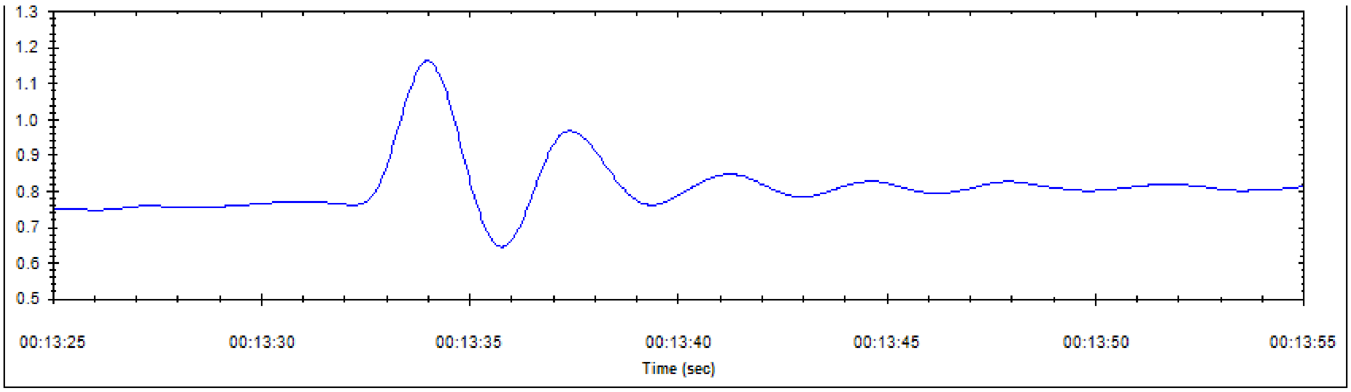

Figure F.63: Alberta Area Phase Angle with Respect to Center Point

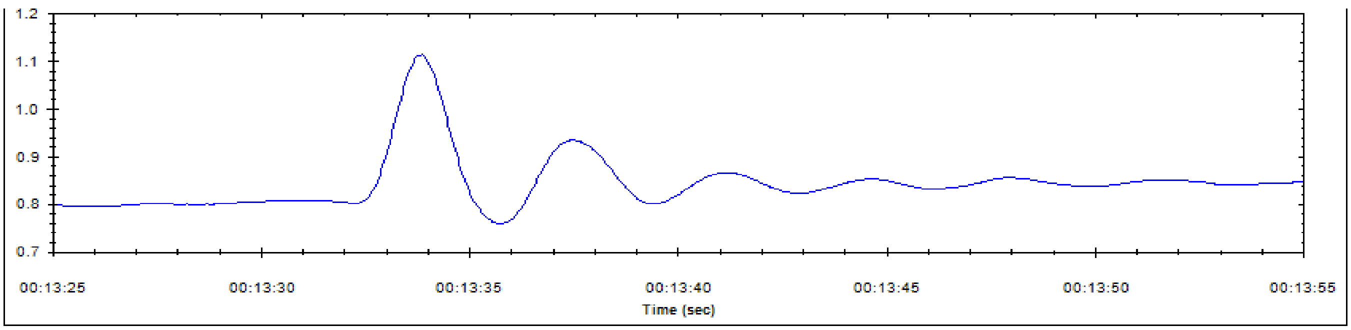

Figure F.64: British Columbia Area Phase Angle with Respect to Center Point

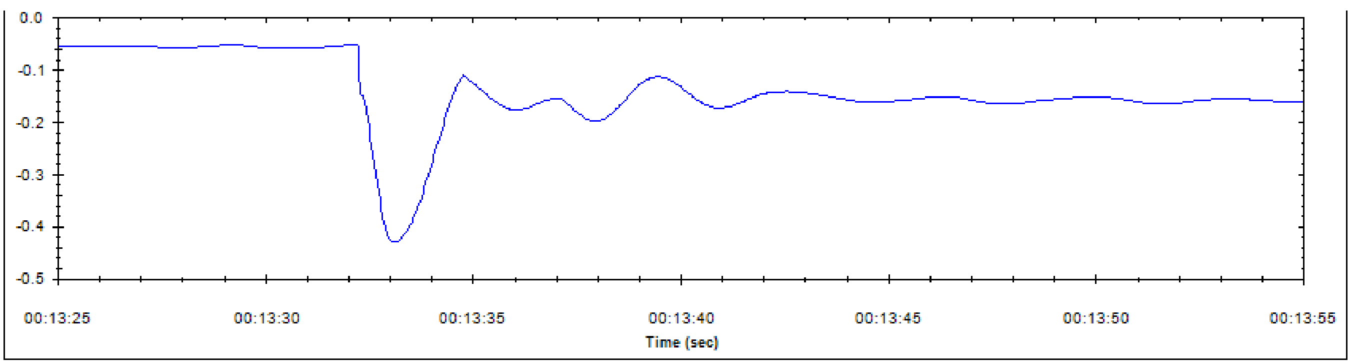

Figure F.65: Southern California Area Phase Angle with Respect to Center Point

To fit the ringdown analysis to the event, the analyzers utilized the bus frequency signals provided by the RCs to similarly relate the signals to a center point. The analyzers chose an analysis window from time stamp 00:13:37 to 00:13:45 in order to capture the ringdown event while mitigating the nonlinear effects of the generator trip reported on FNET 00:13:30. The analysis window is demonstrated in **Figure F.66.**

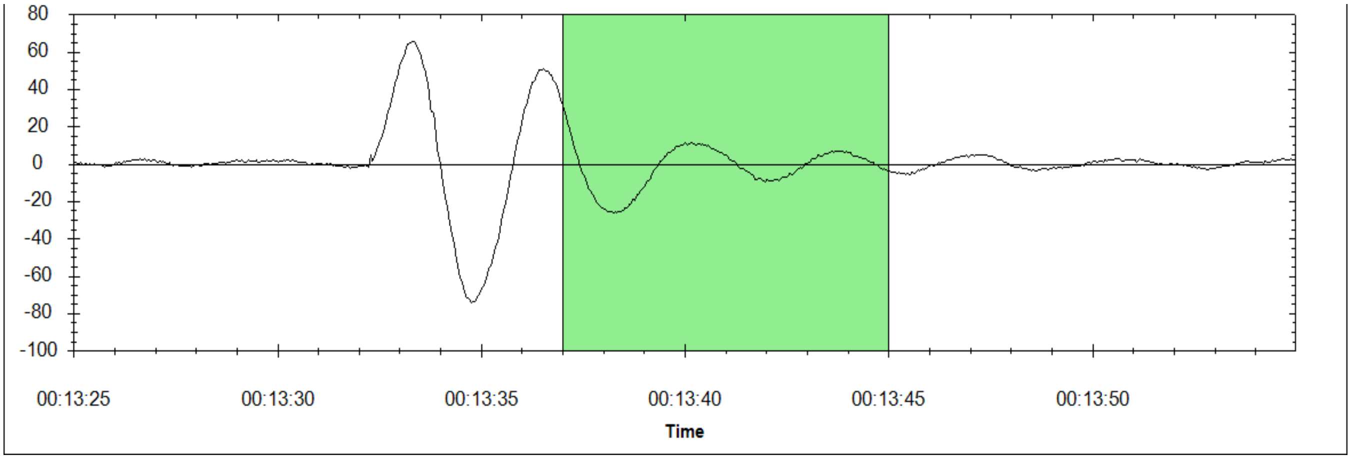

Figure F.66: Ringdown Analysis Window from 00:13:37 to 00:13:45

In order to determine whether the signal match was adequate, the reconstructed signals and their comparison to the original signal are used. If the signal match proves to be poor, settings were adjusted in order to have a better match, providing the results. Figures F.67–F.69 demonstrate the signal match between the original and reconstructed signal.

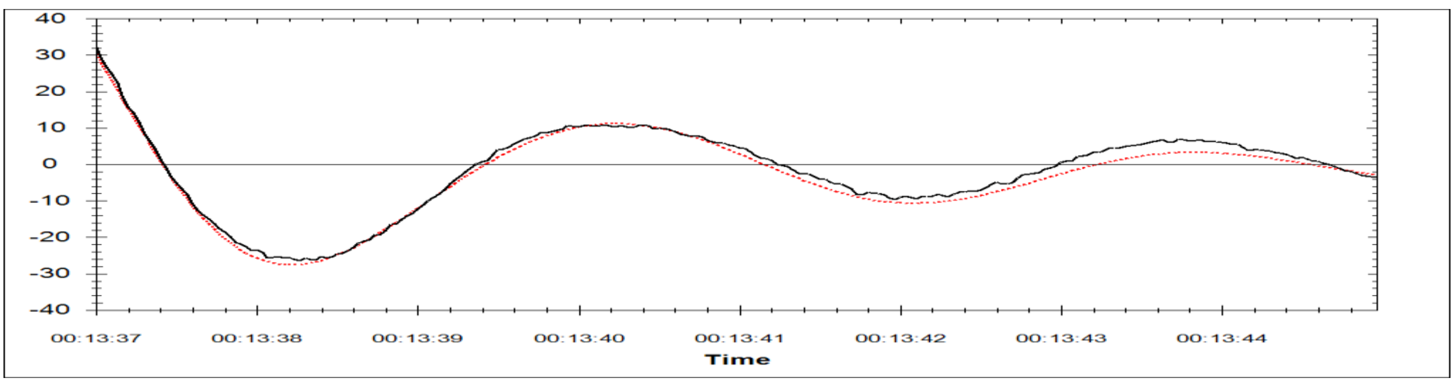

Figure F.67: Alberta Reconstructed and Original Signals

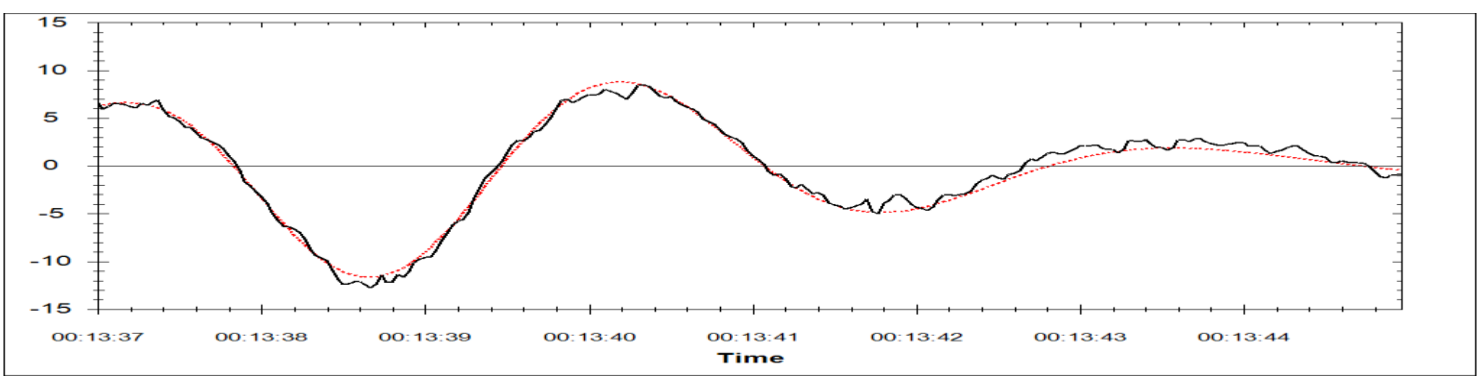

Figure F.68: British Columbia Reconstructed and Original Signals

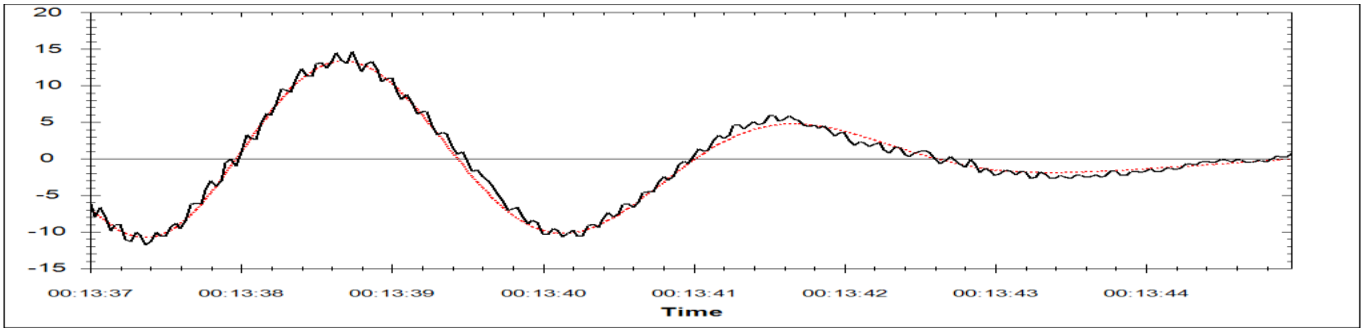

Figure F.69: Southern California Reconstructed and Original Signals

Table F.7 provides the summary of the HTLS results from the analysis. Modes with a relative energy less than 10% are not shown. A total of 270 signals were included in the analysis and all other software engines indicate an agreement for the listed modes. The total square error for the HTLS analysis was 471 mHz. A link to the *Frequency Disturbance Report* can be found on the UTK website.[18]

Table F.7: Dominant Modes		
Frequency (Hz)	Damping (%)	Total Energy (%)
0.27	17.5	64
0.40	18.3	36

The mode shapes for the listed mode in Table F.7 can be found in Figures F.70 and F.71. The 0.24 Hz mode shape accurately depicts the NS Mode B and confirms the results from the previous WI Events. The 0.4 Hz mode shape looks similar to the 0.5 Hz mode shape in the Exploratory Analysis section. The shape is depicted as an interaction between may separate areas with the North and South regions of the Mountain and Pacific regions interacting with each separate end. The North Mountain swings against both the North Pacific and South Pacific regions and the South Mountain region also swings against both the North and South Pacific regions.

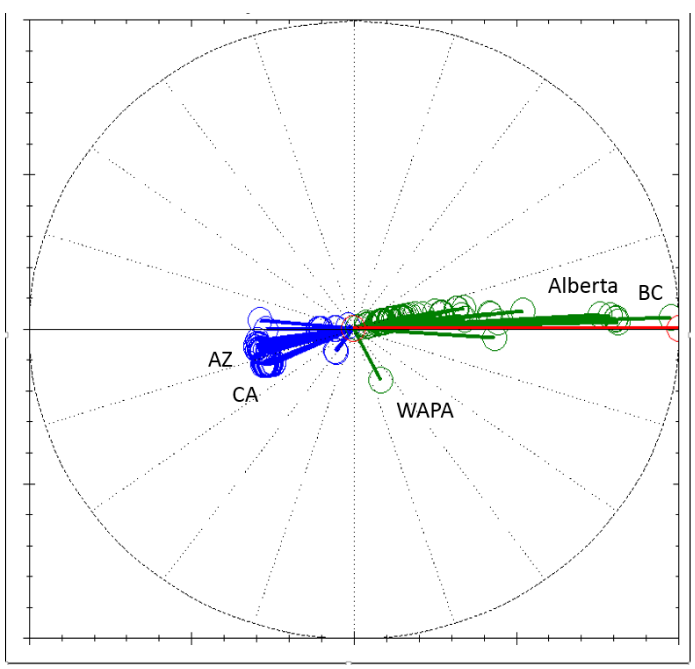

Figure F.70: Mode Shape for 0.27 Hz Mode

[18] Frequency Disturbance Report

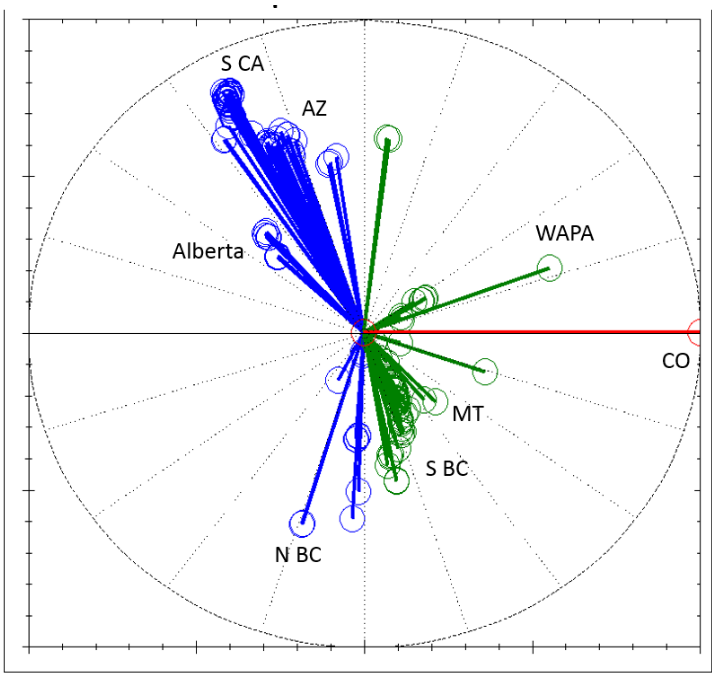

Figure F.71: Mode Shape for 0.4 Hz Mode