Center for Commercialization of Electric Technologies (CCET)

Discovery Across Texas Project

Final Report on

Wind Characteristics

Oscillation Data Mining Study

Submitted to:
Milton Holloway, Ph.D.
mholloway@electrictechnologycenter.com

Prepared by:

Electric Power Group

John W. Ballance
Prashant C. Palayam

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CCET 3.1.3, Task C

1. Introduction

The Center for Commercialization of Electric Technologies (CCET) was awarded contract DE-OE0000194 by the Department of Energy to perform the Discovery Across Texas demonstration project. Electric Power Group, LLC (EPG) received a sub-award from CCET to provide professional services to perform, among other things, an analysis to identify unknown oscillations from existing connected wind generators in the Electric Reliability Council of Texas (ERCOT) grid to prevent system vulnerability and customer complaints. Texas has the greatest amount of wind generation on-line in the nation and attains a new wind production record every year. Increasing wind production with installation of wind controllers poses operating challenges for ERCOT. One of the challenges faced by ERCOT is presence of high/low frequency oscillations from wind generators driven by control systems with a bad setting. The wind farms are embedded with electronic controllers to monitor wind output and manage voltage. These fast responding wind controllers with a bad setting or bad design introduce high/low frequency control system oscillations either intermittently with high energy or consistently with low energy which can plausibly cause the following:

1. Voltage fluctuations at the distribution level power systems.
2. Damage to motor and pumps at homes and residential circuits.
3. To drive nearby wind farms to oscillate at the same frequency and damage nearby wind farm turbine blades and shafts.
4. Interact with other conventional generation units such as coal, natural gas etc., in the grid to oscillate at the same frequency and cause significant forced damage to mechanical parts such as generator shafts.

This analysis summarizes the investigation on examining the Phasor data from nearby wind generators for three years and identification of unknown oscillations. The nearby location with the highest occurrence of those oscillations are identified and labelled as critical locations to monitor in real-time for early detection and mitigation. Based on the occurrence of each mode pattern and its associated energy level spanning over three years, the report groups the oscillations and provides guidelines for ERCOT to help prevent grid vulnerability and customer complaints.

2. Executive Summary

Texas has the greatest amount of wind generation on-line in the nation and attains a new wind production record every year. Increasing wind production with installation of wind controllers poses operating challenges for ERCOT. One of the challenges faced by ERCOT is presence of high/low frequency oscillations from wind generators driven by control systems with a bad setting. The wind farms are embedded with electronic controllers to monitor wind output and manage voltage. These fast responding wind controllers with a bad setting or bad design introduce high/low frequency control system oscillations either intermittently with high energy or consistently with low energy. The early detection and mitigation of emerging oscillations in real-time is crucial to ensuring reliable operation of grid. This sets the stage for baselining the oscillations from nearby wind generators leveraging the existing and installed Phasor Measurement Unit (PMU) locations measuring grid metrics sampling at 30 frames per second.

Hence this study was proposed to investigate:

1. Other unknown oscillations from wind generators.
2. Identify the locations with highest occurrence of those oscillatory modes.
3. Precursors (if any) for such occurrences and the associated energy output.
4. Frequency band and Minimum Energy for additional monitoring.

The detection of unknown oscillations from phasor data was done spanning three years using EPG's Phasor Data Mining Tool. The Tool enabled automatic scanning through the data in periodic intervals, and records the incidents of detected oscillations with damping and energy levels time-stamped for each PMU location.

This analysis was based on six PMUs located nearby wind farms in the ERCOT Interconnection. The Phasor Data Mining Tool was configured with needed algorithm settings to scan through six PMU locations for different frequency bands ranging from 0.1Hz to 15Hz. The measurements including Frequency, Voltage Phasor and Current Magnitude under each PMU were examined to record detected modes every minute and calculated damping and energy associated with each mode. The results were time-stamped and tagged to the PMU locations to identify the source of the oscillations. The Tool was asked to discard modes with damping greater than 8%, regardless of the detected energy level. The Tool leveraged the PMU status information to clean bad data to avoid false detections. The detection results from the tool were parsed and post processed through MATLAB scripts to rank the oscillatory modes with the highest occurrence and highest energy. These results were then examined to identify any relationship between each Mode Occurrence and the corresponding Regional wind data. The highest energy of a mode was extracted and compared with the Mode Occurrence to baseline the minimum energy required to monitor in real-time and also to differentiate modes related to wind production versus modes driven by control systems or setting change in control systems.

Some of the key findings are as follows:

1. The study identified 10 different ERCOT Oscillatory Modes.
2. The occurrence of 2 modes appears to be related to wind production – 0.9Hz (Tonkawa) & 2.7Hz (Longshore).
3. The occurrence of 4 modes appear to be related to control system settings changes – 1.5Hz (Gulf Wind), 1.7Hz (Odessa), 2Hz (Gulf Wind), 3.2Hz (Matador).
4. The occurrence of 3 modes appear to be related to the presence of wind generation and control systems - 5.0Hz (Gulf Wind) ,5.4Hz (Matador & Longshore), 6.0Hz (Matador).
5. The occurrence of 1 mode appears to be a local oscillation caused by to topology change or mis-tuning of the wind generator control system – 0.6Hz (Matador).

This study concludes that four modes appear consistently for three years and are still present. There are four other modes that appear intermittently with high energy. There are other two modes that appeared consistently for the first two years, but were not detected in 2014. The report provides insights on the Real Time Dynamics Monitoring System[1] (RTDMS®) configuration for monitoring certain modes in real-time to detect and mitigate the oscillations. The modes which appear only sporadically may need additional review by ERCOT with the plant owners to determine the root cause and evaluate the need for additional monitoring.

3. Goals & Methodology

The objective of this analysis was to identify unknown oscillations from existing connected wind generators in the Electric Reliability Council of Texas (ERCOT) grid to prevent system vulnerability and customer complaints. Utilizing six different PMUs located nearby wind generators during the period of 2012-2014, the study set five goals:

1. Build a Phasor Data Mining Tool that can scan through the phasor data, detect low damped oscillatory modes and record the associated damping & energy value.
2. Using the results from the mining tool, calculate following monthly statistics for each mode
    a. Mode Occurrence (in percent of time)
    b. Highest Energy Value
    c. Timestamp and PMU measurement with the Highest Energy Value
3. Identify the nearby PMU location that had highest mode occurrence.
4. Correlate Mode Occurrences with Regional Wind data to determine the type of oscillation – Related to Wind Production or Driven by Control Systems.

[1] Built upon GRID-3P® platform. US Patent 7,233,843, US Patent 8,060,259, and US Patent 8,401,710.

5. Baseline Oscillation characteristics – Minimum Energy Level and Frequency Band for additional monitoring in real-time.

Figure 1 shows the flowchart that describes the workflow of the analysis study. The different steps in the analysis study were:

Step 1 Gather phasor data from six different PMU locations for three years in a database.
Step 2 Setup Jobs in the Phasor Data Mining Tool to connect to the database and scan through the data with user-defined configuration.
Step 3 Export the Mining Tool results from the results database into a CSV file.
Step 4 The CSV file containing results for all PMU measurements was then parsed for post processing in MATLAB.
Step 5 MATLAB script was written to calculate monthly statistics on mode occurrence and filter oscillatory modes with low occurrence and low energy.
Step 6 Export post processed results for each PMU measurement
1. Mode Occurrence of each mode
2. Highest Energy for each mode
3. Timestamp of the mode with highest energy

Step 7 Conduct analysis to achieve the goals for this study.

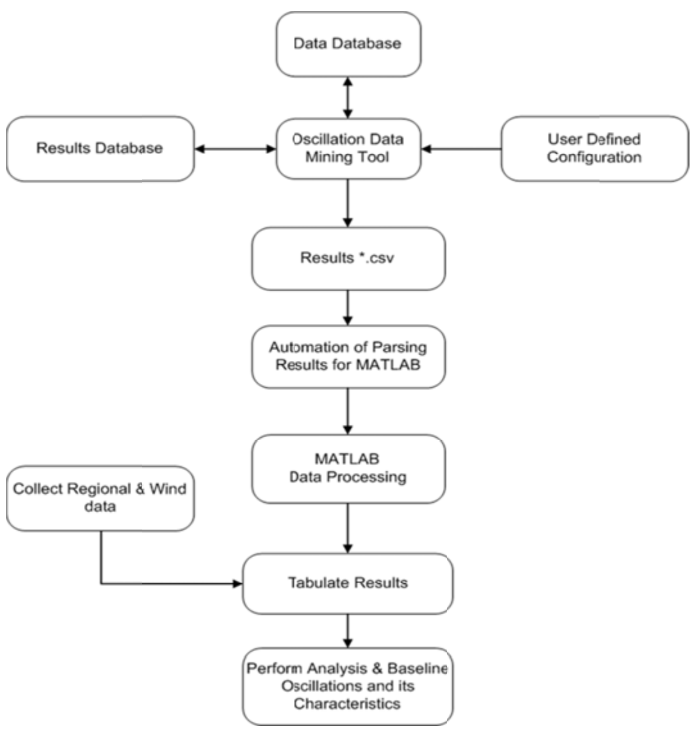

Figure 1. Analysis Work flow

4. Derived Metrics & Calculated Variables

The following results associated with oscillations were collected from the Phasor Data Mining Tool after scanning through the phasor data:

1. Oscillatory Mode (Frequency Value in Hz).
2. Damping associated with Oscillatory Mode (Percentage).
3. Energy level associated with Oscillatory Mode (no unit, Magnitude).

The above sets of results were time-stamped and tagged with the associated PMU measurement. The Tool was configured to output results every minute (sampling of successive 60 second intervals of phasor data).

The variables calculated for this study are:

1. Monthly Average Regional Wind Generation (3 regions)
    a. Wind North = Aggregation (North)
    b. Wind West = Aggregation (Far West, West)
    c. Wind South = Aggregation (South, Coastal Wind)

The metrics derived for this study are:

1. Monthly Mode Occurrence (%) = (Count of minutes having mode/total number of reported minutes) * 100 (e.g. 0.9Hz appeared 42% of time in April 2012)
2. Monthly Highest Energy = Maximum Energy of an oscillatory mode each month

Other information extracted along with monthly statistics is:

1. Timestamp associated with the highest energy
2. PMU measurement associated with mode

5. Phasor Data Mining Tool – Oscillation Candidates

The six different PMU locations that were used in the study were located nearby wind generators, but do not directly monitor the output of individual wind farms, include the following:

1. Odessa
2. Matador
3. Longshore
4. Tonkawa
5. Penascal
6. Gulf Wind

The PMU at substation Killeen Switch was used in the study as a reference for PMU Voltage angle measurements. The signal types from PMU measurements used in the study are as follows:

1. Frequency.
2. Voltage Phasor (Voltage Magnitude & Voltage Angle).
3. Current Magnitude.

The Mining Tool is configured to look for oscillatory modes within one frequency band from 0.1Hz to 15Hz. Bad data in the phasor measurements are removed before scanning for oscillations using the flags set in the Status Signal embedded with PMU measurements C37.118 format. The algorithm settings to scan for oscillations are set in such a way that the output results are reported:

1. Every Minute – The output result for each (study) minute is the algorithm output for the phasor data available in that minute.
2. Modes are discarded with Damping greater than 8%.
3. Energy for each Mode is computed.
4. Minimum Frequency – 0.1Hz.
5. Maximum Frequency – 15Hz.

6. Oscillation Data Mining Tool Performance & Processing

The Phasor Data Mining Tool performs several functions such as data extraction, data cleaning, data calculation and data storage into the results database. The approximate time taken to completely process one minute of phasor data (for multiple PMUs) is approximately 4 seconds. Using this average processing timing, the processing of a full month of phasor data would take approximately 2 days. Figure 2 shows the Tool performance for an operation, 1 Hour, 1 day & 1 Month.

Task	Time
Data Loading **(1 minute of data, All PMU signals)**	3 sec
Data Filtering **Mode Solving** **Result Exporting**	1 sec
Total **(All FrequencyBands)**	**4 sec**
Ideal Example	
1 Hour	4 Min
1 Day	1.6 Hours
1 Week	11.2 Hours
1 Month (31 days)	**2.06 Days**

Figure 2. Phasor Data Mining Tool Performance

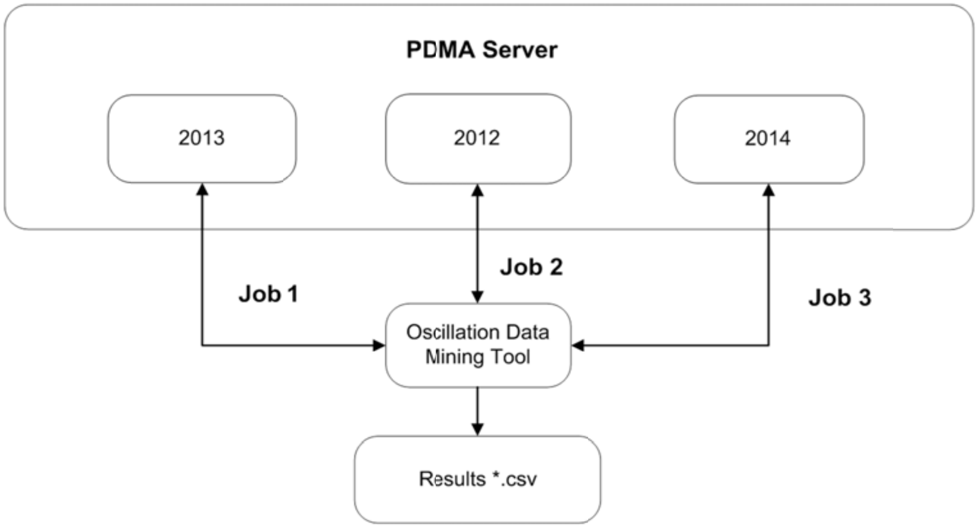

Figure 3. Analysis Work flow

In order to expedite the scanning process to successfully scan a full 3-years' worth of data, three simultaneous processing jobs were established to scan each of the three different years in parallel. The same performance that took two days for 1 Month was achieved for each job if they were setup in different servers. This parallel processing helped expedite the completion of oscillation scanning process in a more effective way instead of scanning one year after another.

7. Oscillation Data Mining Results – Post Processing

The Phasor Data Mining Tool reports results for each study minute which has a detectable oscillatory mode, including its associated damping and energy value time-stamped with PMU measurements. The MATLAB script was written to read the output results of the Phasor Data Mining tool and scan through to populate monthly statistics for each detected mode in each of the PMU measurements. The statistics and metrics are explained briefly in Section 4. It is important for planners and operators to focus on those oscillatory modes that occur most of the time and those modes that occur with high energy. Hence, those oscillatory modes with a monthly occurrence which was less than 20% of the highest occurrence among all the modes observed in all PMU measurements were discarded. Similarly oscillatory modes were discarded where the highest mode energy was less than 20% of the highest energy among all the modes observed in all PMU measurements. The output results from MATLAB post processing include PMU metric identification (name and signal type), oscillatory modes detected, Mode Occurrence, and Highest Energy and associated Timestamps for further analysis studies to accomplish the goals of the project.

The output results for three years from MATLAB post processing are attached to this report as an Excel workbook, "Wind Oscillation Study – Monthly Statistics," The Excel workbook consists of two sheets. The first sheet, "Modes_Aval" contains the modes filtered by highest occurrence, and the second sheet, "Modes_Ene" contains the modes filtered by highest energy. Both sheets include the following information in different columns in the following order: Year-Month, PMU Name, Signal Name, Signal Type, Frequency Range, Monthly Occurrence, Highest Energy, Mode (Associated Oscillatory Frequency value in Hz), and Timestamp (Associated time in UTC). The Highest Energy, Mode & Timestamp are associated with each other.

8. Summary of Identified ERCOT Oscillatory Modes

Figure 4 shows a quick summary of the ten identified oscillatory modes in the ERCOT interconnection, as measured by PMUs located at nearby wind generators. All the modes appeared due to the presence of wind generators, but differed in terms of energy levels and mode occurrence. The Mode occurrence and energy levels provided clues to differentiate between those modes related to wind production and those which appear to be driven by control systems. There appear to be four modes (0.9Hz, 5.0Hz, 5.4Hz & 6.0Hz) that are consistent in occurrence spanning three years and continue to be present. The rest of the modes appear to fall into two categories of intermittency. The 0.6Hz & 2.7Hz modes appeared constantly for a period of time (four months and twenty four months, respectively), but then they disappeared, and have not reoccurred. Their disappearance may indicate a relationship between the oscillation and a topology change or a change in the tuning of the generator controls. These modes need further investigation to review their disappearance for additional monitoring. The second category of oscillations appears to be intermittent and shows high energy when they occurred. These modes need additional monitoring to identify their nature and initiating factors. The 1.7Hz, 1.5Hz, 3.2Hz & 2Hz belong to this second category and appear to be driven by temporary changes in the control systems settings of the nearby generators.

Figure 5 shows the list of ten oscillatory modes with the nearby location of wind generators that saw the highest occurrence of each mode. The 0.9Hz and 2.7Hz mode occurrences followed the regional wind pattern and appeared to be related to wind production. The monthly highest energy levels gathered across three years tracked the level of occurrence, providing further indication that the respective modes were related to wind production. The monthly highest energy levels of the 5.0Hz, 5.4Hz & 6.0Hz modes remained flat and didn't appear to vary in relationship with changing levels of regional wind production, except for the 6.0Hz mode, which had relatively high energy during certain periods of time. This mode deserves additional monitoring. The highest energy levels of these modes appear to be driven by settings change in control systems provided, and the baseline energy levels can be used as a reference for the minimum energy to set for additional monitoring (alarming) in real-time. It is also evident that there are several modes observed from a PMU location nearby to wind generators.

#	Mode (Hz)	2012	2013	2014	Oscillation Type
1	0.6	Till March	Absent	Absent	Local
2	0.9	Present	Present	Present	Wind Production Related
3	1.5	Only in April	Absent	Absent	Control Systems
4	1.7	4 Months	Absent	Absent	Control Systems
5	2.0	Absent	April	Absent	Control Systems
6	2.7	Present	Present	Absent	Wind Production Related
7	3.2	4 Months	Absent	Only in Jan	Control Systems
8	5.0	Present	Present	Present	Control Systems
9	5.4	Present	Present	Present	Control Systems
10	6.0	Present	Present	Present	Control Systems

Figure 4. Presence/Absence of 10 Oscillatory Modes over 3-years

#	Mode (Hz)	Nearest PMU	Related to Wind Production	Highest Energy Level
1	0.6	Matador	No	Low Energy & Flat
2	0.9	Tonkawa	Yes	High Energy & Tracking Occurrence
3	1.5	Gulf Wind	No	Low Energy
4	1.7	Odessa	No	High Energy
5	2.0	Gulf Wind	No	Low Energy
6	2.7	Longshore	Yes	High Energy & Tracking Occurrence
7	3.2	Matador	No	High Energy
8	5.0	Gulf Wind	No	Low Energy & Remained Flat
9	5.4	Matador, Longshore	No	Low Energy & Remained Flat
10	6.0	Matador	No	Intermittent High Energy

Figure 5. Ten Oscillatory Modes – Location, Type, and Energy Level Pattern

9. Detailed Description of 10 Identified Modes

This section of the report describes the four types of oscillatory modes identified in the ERCOT interconnection associated with nearby wind generators. The four types of oscillatory modes are:

1. The Occurrence of 2 modes appears to be related to wind production – 0.9Hz (Tonkawa) & 2.7Hz (Longshore).
2. The Occurrence of 4 modes appear to be related to control system settings changes – 1.5Hz (Gulf Wind), 1.7Hz (Odessa), 2Hz (Gulf Wind), 3.2Hz (Matador).
3. The Occurrence of 3 modes appear to be related to the presence of wind generation and related to wind generation control systems - 5.0Hz (Gulf Wind) ,5.4Hz (Matador & Longshore), 6.0Hz (Matador).
4. The Occurrence of 1 mode appears to be a local oscillation due to a topology change or tuning of wind generators – 0.6Hz (Matador).

<u>Mode 2: 0.9Hz</u>

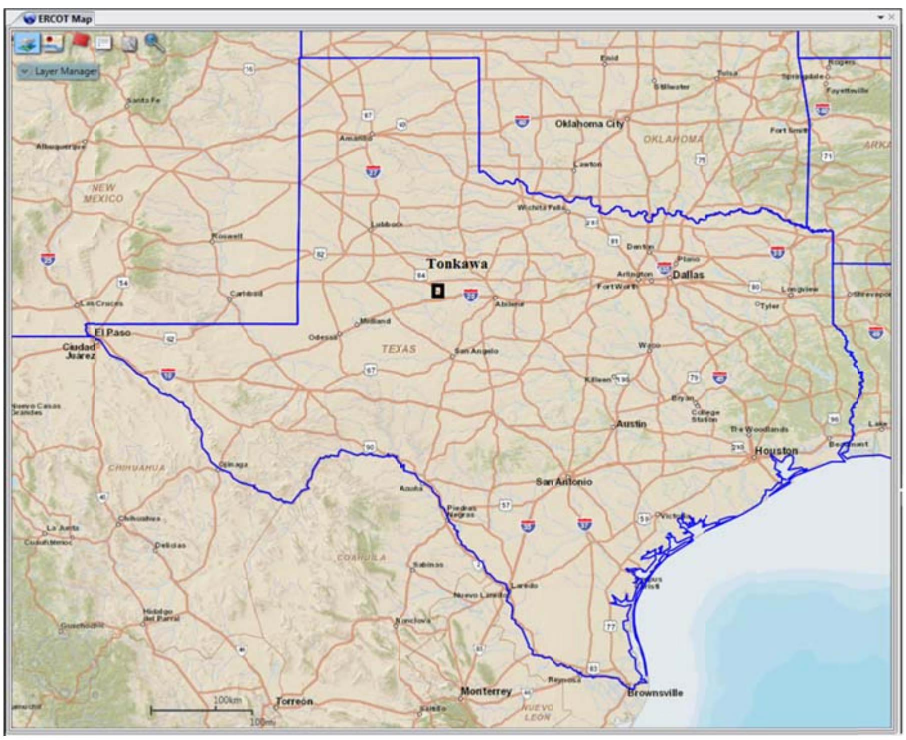

Figure 6. Mode 2 – PMU location

Figure 6 shows the PMU location in the ERCOT interconnection that had consistent occurrence of the 0.9Hz mode spanning 3-years and continues to be present. The Mode showed up in the current magnitude signal measurement in the Tonkawa substation located nearby wind generators including Pyron, Champion, Roscoe, Inadale. Figure 8 shows the trend of the 0.9Hz mode occurrence in the Tonkawa current magnitude signal over 3-years. The maximum occurrence of 0.9Hz mode appeared for 53% of time in June 2014, and minimum occurrence of the same mode appeared 22% of time in December 2013. The average occurrence over all 3-years is approximately 42% of the time each month. Figure 7 shows the comparison between the mode occurrence of 0.9Hz and the monthly average west wind production in MW from January 2012 to April 2013. The trend of Mode Occurrence & Average West Wind have similar patterns and provides a first indication that 0.9Hz is likely related to wind production. The mode occurrence reduced from 40% to 30% when the average wind production showed reduction from 3000MW to 1600MW in August 2012, suggesting that Mode 0.9Hz is related to wind production. This relationship is based on west wind generation (an aggregation of wind production) - wind production solely at Tonkawa was not available for comparison. Similarly, the mode occurrence increased to 48% in April 2013 when the average wind production increased to 3500MW in the same month.

This mode appears to be wind production related and occurs consistently every month. It is noted that the energy level of the mode closely tracks wind production (e.g., increases with increasing levels of wind production, etc.). Figure 8 shows the comparison of the mode occurrence to the highest energy of the mode during each month spanning 3-years. The mode obtained its maximum highest monthly energy of approximately 12 in February 2013 and the minimum highest monthly energy in September 2013 of approximately 0.5. It is recommended that ERCOT monitor this mode in real-time with the following mode meter configuration to detect increasing energy levels during high wind production.

- PMU Signal: Tonkawa Current Magnitude.
- Minimum Frequency = 0.85Hz.
- Maximum Frequency = 1.2Hz.
- Minimum Energy = 2.
- Damping = 8%.

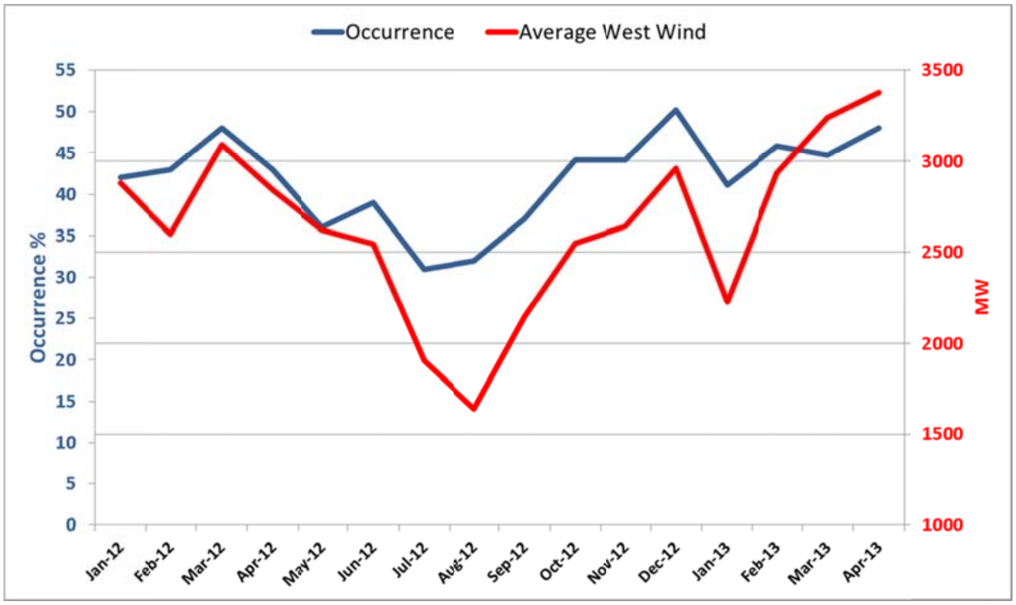

Figure 7. Mode 2 – Mode Occurrence vs. Regional West Wind

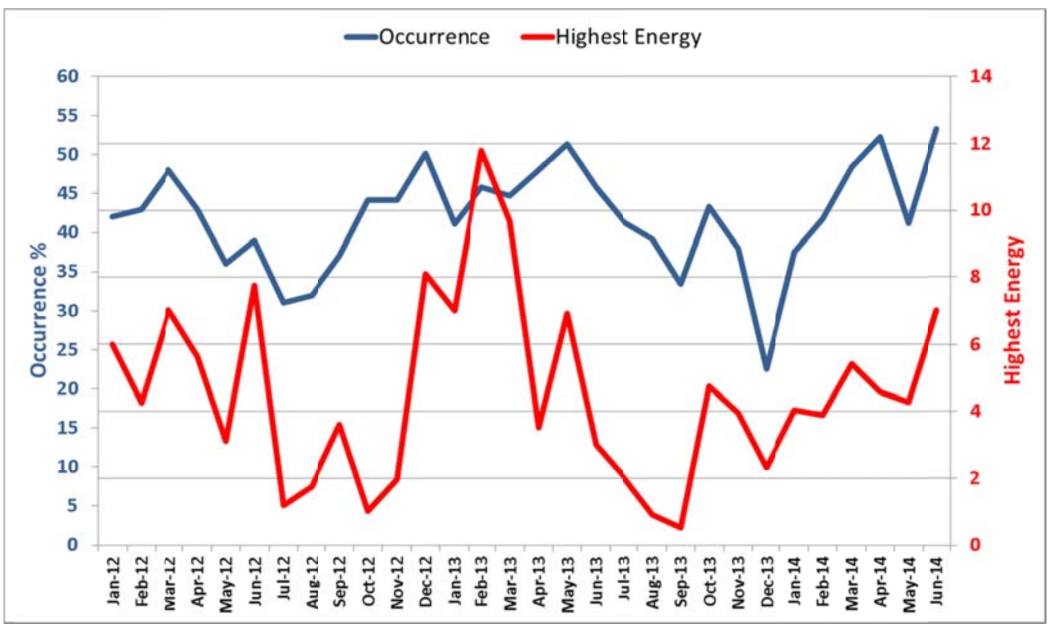

Figure 8. Mode 2 – Mode Occurrence vs. Highest Energy

Mode 6: 2.7Hz

Similar to 0.9Hz, the study discovered another mode at 2.7Hz related to wind production. Figure 9 shows the PMU location in the ERCOT interconnection that had the most consistent occurrence of the 2.7Hz mode. The mode showed up in the current magnitude signal measurement in the Longshore substation located nearby generators including Panther Creek.

Figure 11 shows the trend of this 2.7Hz mode occurrence in the Longshore current magnitude signal over 2-years, and then suddenly disappearing starting January of 2014. The maximum occurrence of 2.7Hz mode appeared for 34% of the time in May 2013, and minimum occurrence of the same mode appeared 9% of the time in July 2013. The average occurrence in first 2-years is approximately 20% of the time each month. Figure 10 shows the comparison between mode occurrence of 2.7Hz and monthly average west wind production in MW from January 2012 to April 2013. The trends of mode Occurrence & Average West Wind have similar patterns and provide a first indication that the 2.7Hz mode is likely related to wind production.

This mode is no longer present and its disappearance may be related to the addition of new CREZ transmission lines near Longshore or the re-tuning of machines at Panther Creek. Figure 11 shows the comparison of the mode occurrence to the highest energy of the mode during each month spanning the first 2-years. During the mode occurrence, the highest energy was not relatively high as compared to 0.9Hz. It is recommended that ERCOT review the disappearance of the mode with wind owners and determine the root cause to evaluate the need for additional monitoring.

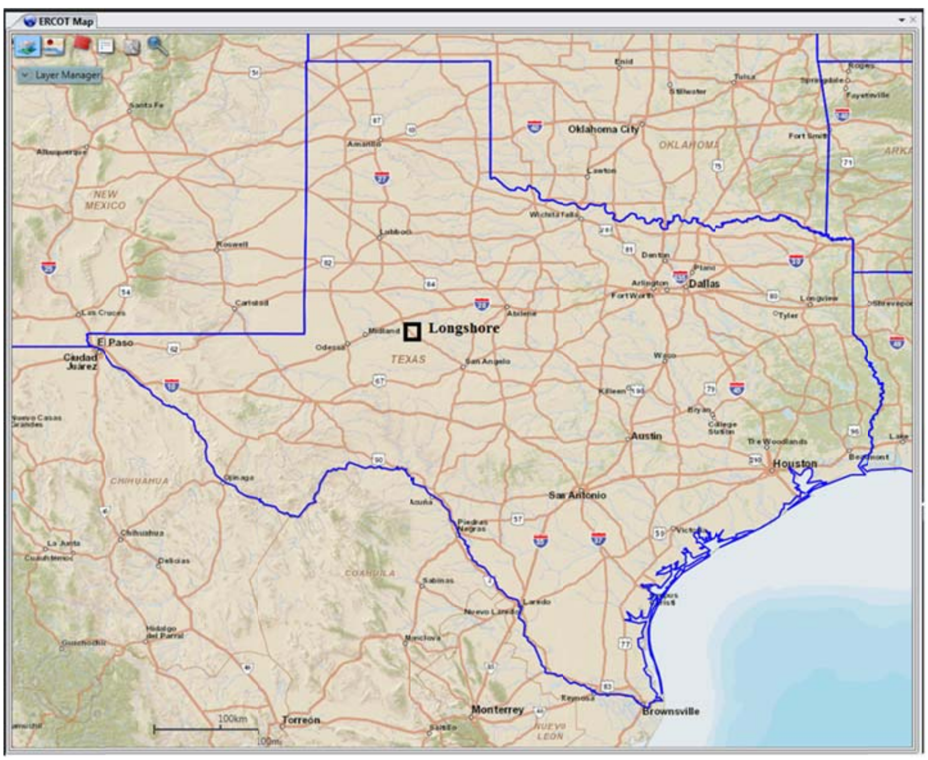

Figure 9. Mode 6 – PMU Location

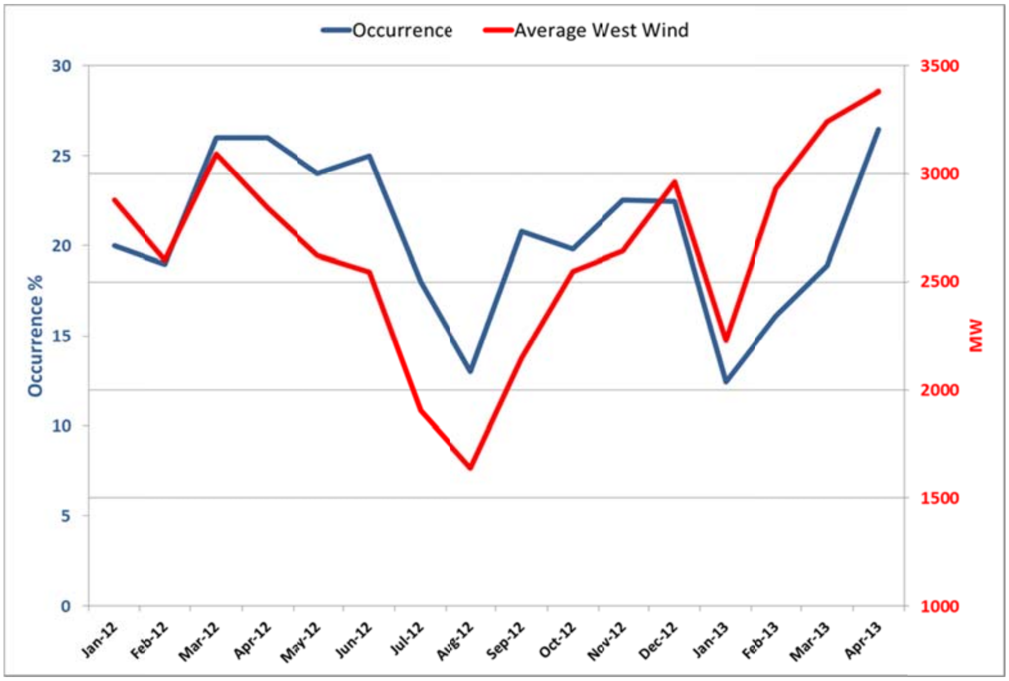

Figure 10. Mode 6 – Mode Occurrence vs. Regional West Wind

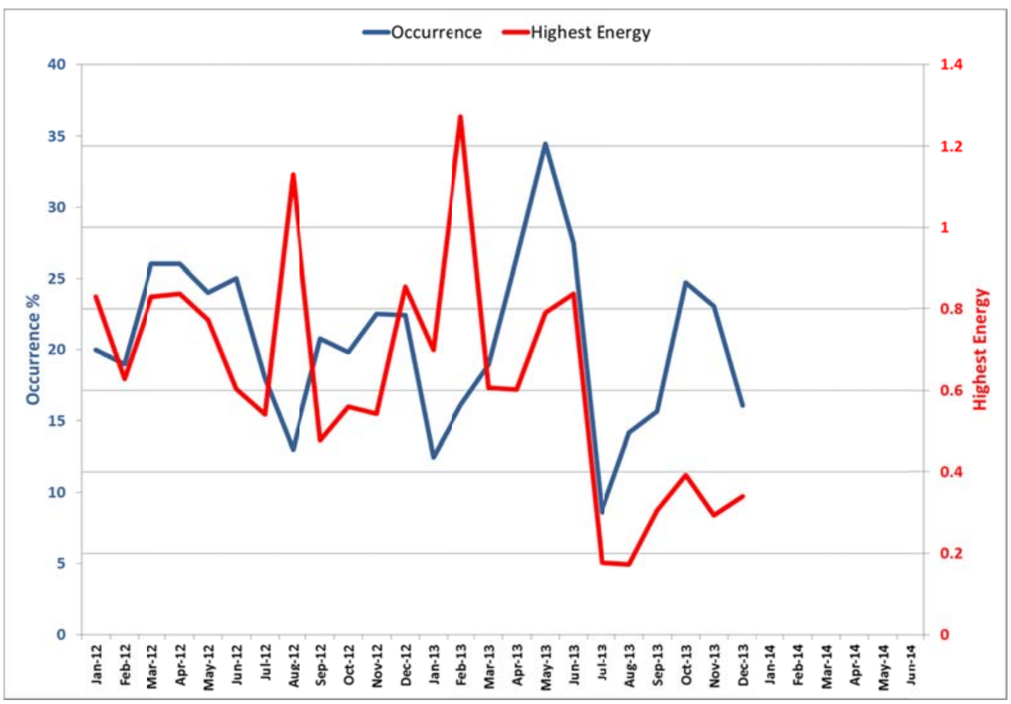

Figure 11. Mode 6 – Mode Occurrence vs. Highest Energy

Mode 8: 5.0Hz

Figure 12 shows the six different PMU locations in the ERCOT interconnection that showed the occurrence of the 5.0Hz mode. Of these six locations, Gulf Wind & Penascal in the Valley saw the highest and most consistent occurrence of this mode. This mode showed up in the Voltage Magnitude, Voltage Angle & Frequency signal measurements in the Gulf Wind & Penascal substations, both of which are located at nearby wind generators including Gulf Wind & Penascal. Figure 14 shows the trend of the 5.0Hz mode occurrence in the Gulf Wind Voltage magnitude signal over 3-years. The mode appeared every month in all three years except first three months of 2012 and the month of March 2013. The maximum occurrence of the 5.0Hz mode was 57% of the month in May 2014, and the minimum occurrence was 0.1% of the month in December 2012.

Figure 13 shows the comparison between the mode occurrence of 5.0Hz from all signal measurements of Gulf Wind and the monthly average south wind production in MW from January 2012 to April 2013. The trend of mode Occurrence from all signal measurements does not have pattern similar to the Average South Wind MW, and thus it appears that this mode is likely not related to wind production. Figure 14 shows the comparison between mode Occurrence and monthly highest energy of the 5.0Hz mode. The highest energy level remained flat and low; not changing with different levels of south wind production, suggesting that the mode is likely driven by the control systems of the nearby wind generators. The mode appears to be related to the operation (simply being on-line) of the wind generation and not to the level wind production. During the span of 3-years, the energy level of this mode remains consistently low. The mode obtained its maximum highest monthly energy of approximately 0.09 in May 2013, and minimum highest monthly energy in December 2012 was approximately 0.00015.
It is recommended that ERCOT review this 5.0Hz oscillation with wind owners to determine the root cause, and to evaluate need for additional monitoring and possible mitigation.

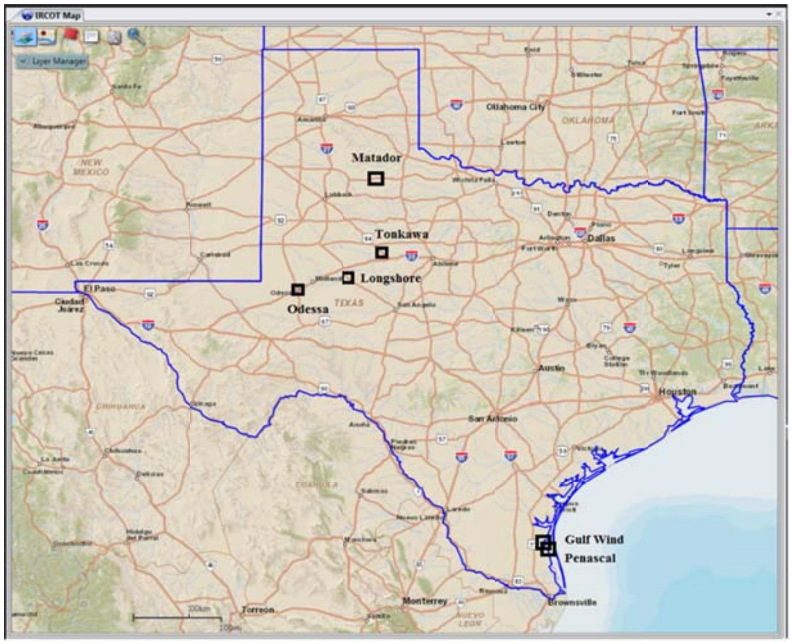

Figure 12. Mode 8 – PMU locations

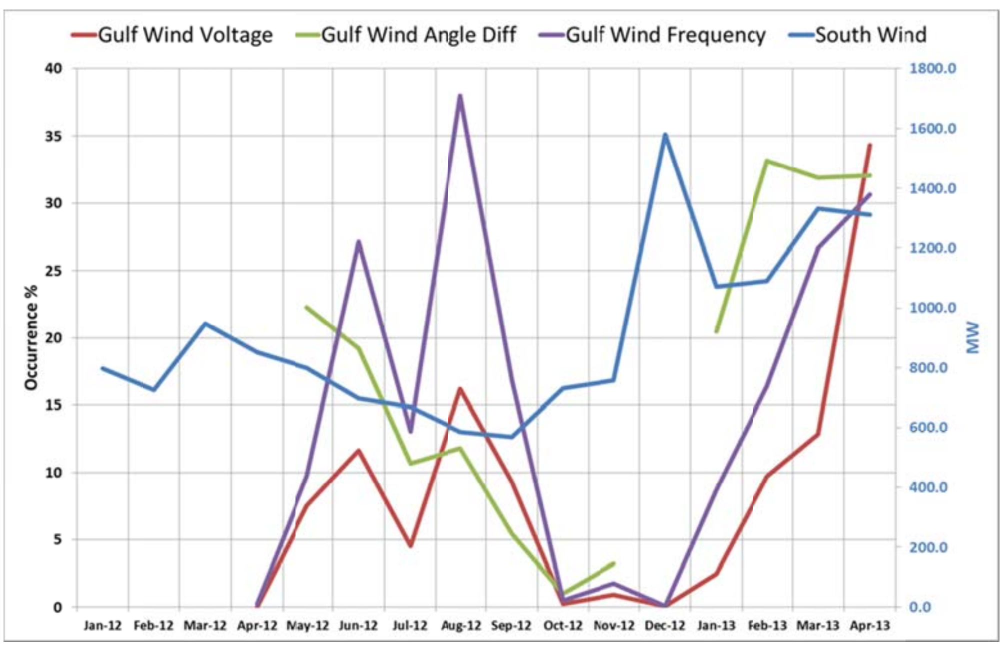

Figure 13. Mode 8 – Mode Occurrence vs. Regional South Wind

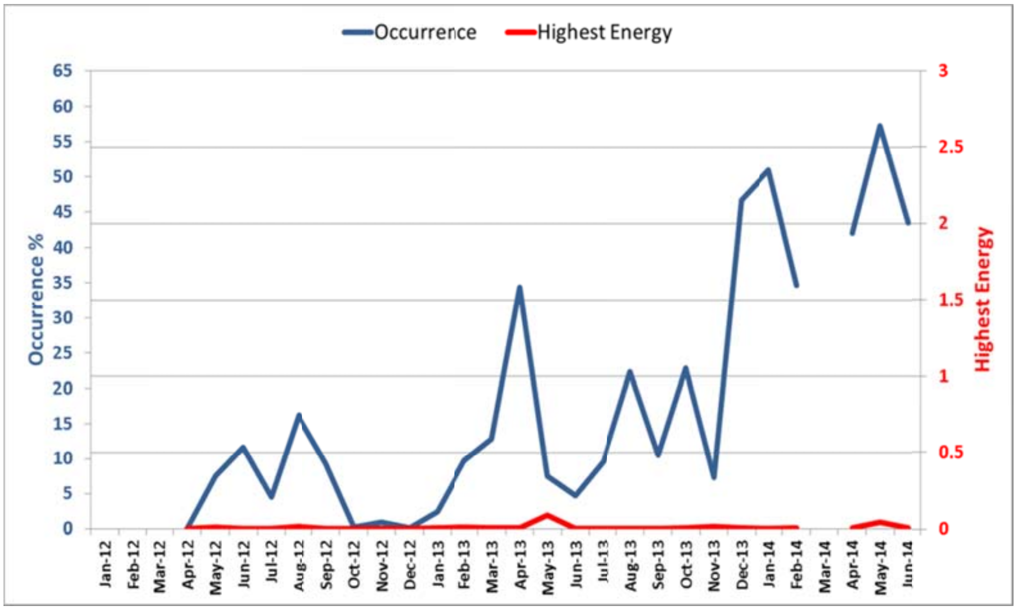

Figure 14. Mode 8 – Mode Occurrence vs. Highest Energy

<u>Mode 9: 5.4Hz</u>

Similar to the 5.0Hz mode, the study discovered another mode at 5.4Hz at six different locations as shown in Figure 15. The highest occurrence of the mode showed up in both West Texas and the Panhandle regions of the ERCOT interconnection. This mode exhibits patterns similar to the 5.4Hz mode occurrence. The Voltage Magnitude signal measurement at Longshore substation in the West Texas region showed the highest occurrence of the mode in West Texas (Odessa and Tonkawa also showed the mode, but at lower energy levels). Figure 20 shows the mode occurrence of 5.4Hz at Matador and Longshore indicating that the 5.4Hz mode has different drivers in the two regions. Hence, Longshore at West Texas and Matador at Panhandle were identified as critical locations to monitor 5.4Hz mode.

Similar to the 5.0Hz mode at Gulf Wind and Penescal, the 5.4Hz mode at Matador appears to be driven by the control systems of the nearby wind generators, and not by the level of wind production. The same forensics for mode 5.0Hz was obtained using the Figures 16 & 17. Figure 16 shows the comparison between the mode occurrence of 5.4Hz and the monthly average north wind production in MW from January 2012 to April 2013. Figure 17 shows the comparison between the mode Occurrence and the monthly highest energy of the 5.4Hz mode. The same relationship appears to be true for this 5.4Hz mode at Longshore as shown in figures 18 & 19. The highest energy level trend of the 5.4Hz mode at Longshore remained flat and low; not changing with different levels of wind production, even though the mode occurrence interestingly tracked the west wind production. It is recommended that ERCOT review the 5.4Hz oscillation with wind owners to determine the root cause, and to evaluate the need for additional monitoring and possible mitigation.

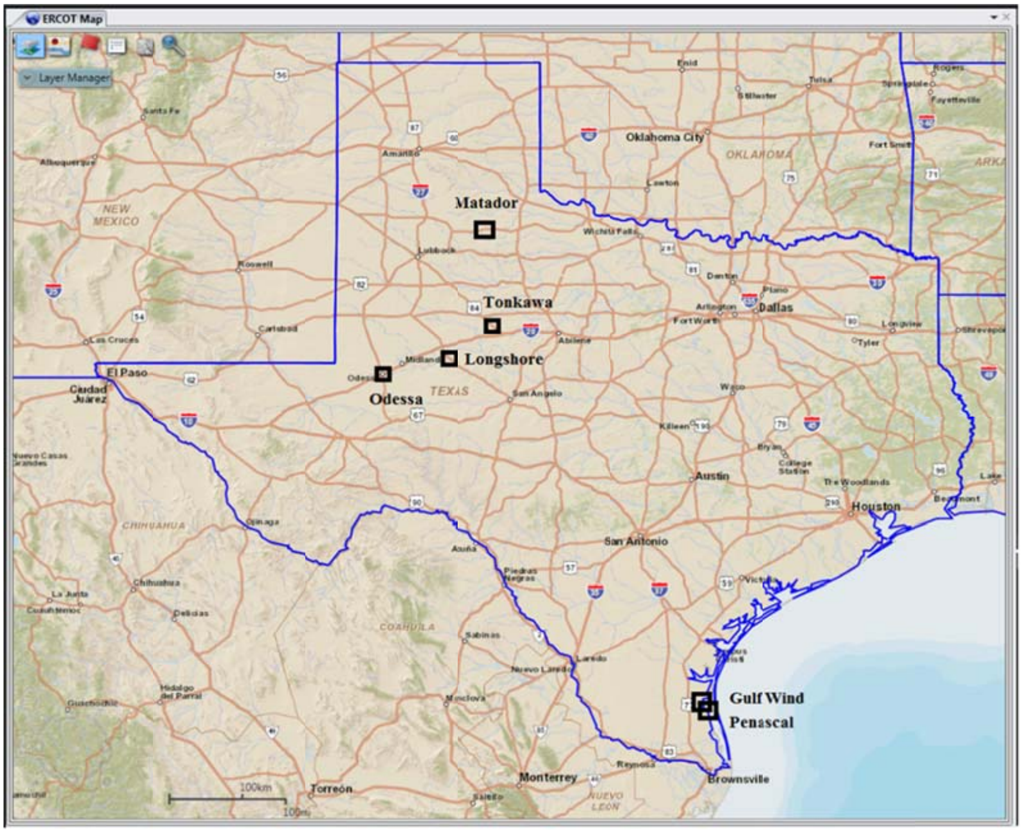

Figure 15. Mode 9 – PMU Locations

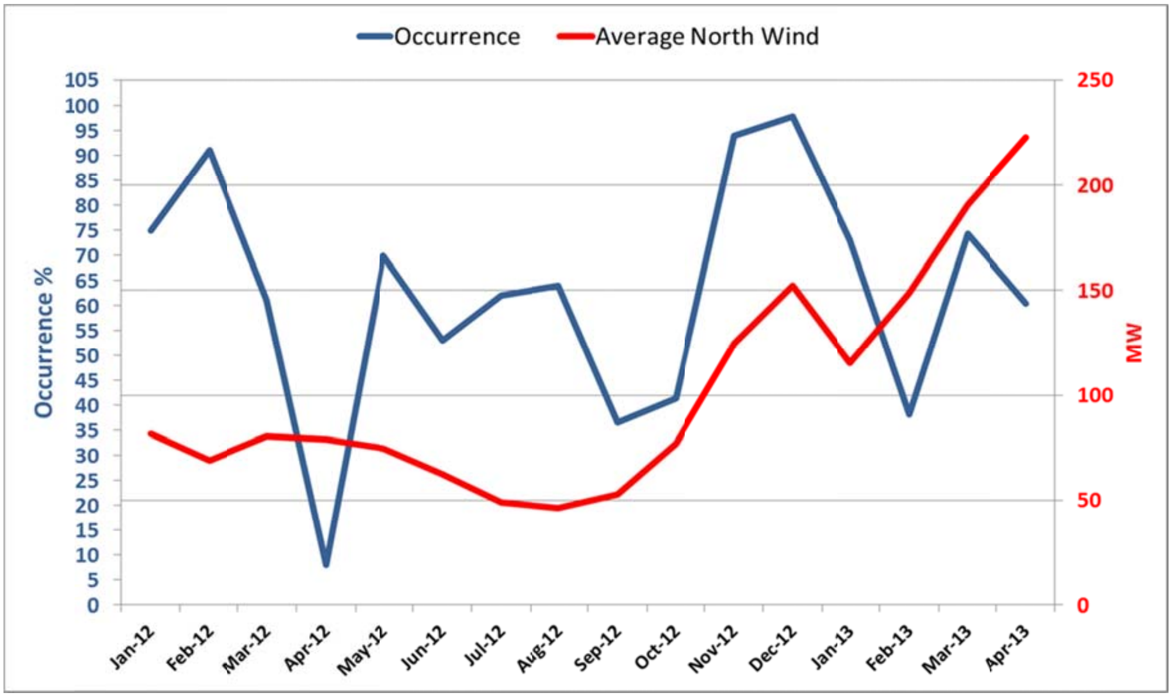

Figure 16. Mode 9 @ Matador – Mode Occurrence vs. Regional North Wind

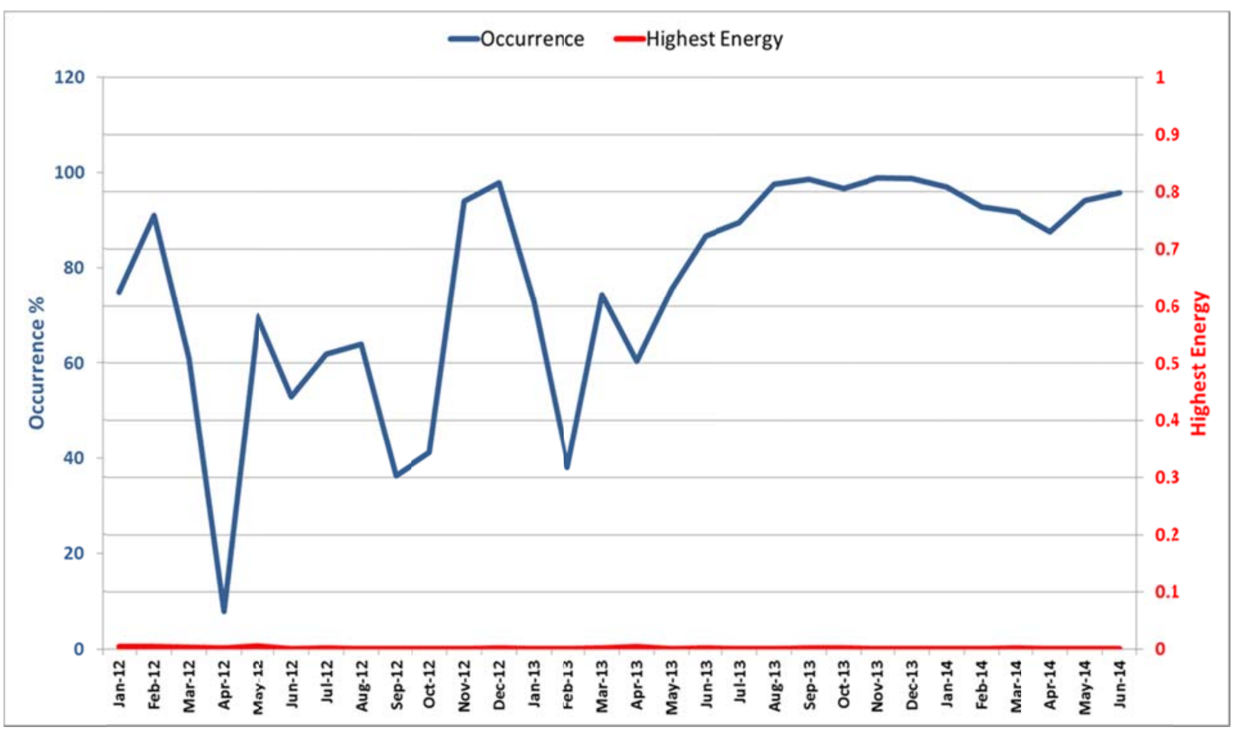

Figure 17. Mode 9 @ Matador – Mode Occurrence vs. Highest Energy

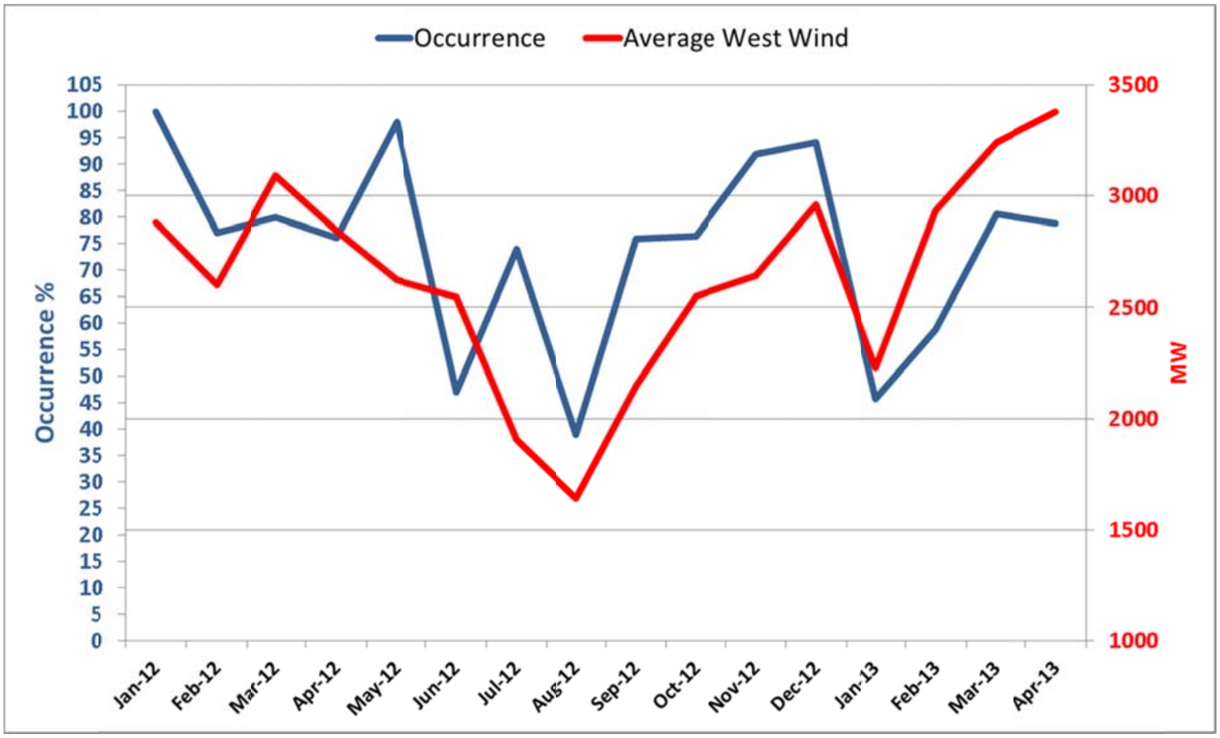

Figure 18. Mode 9 @ Longshore – Mode Occurrence vs. Regional West Wind

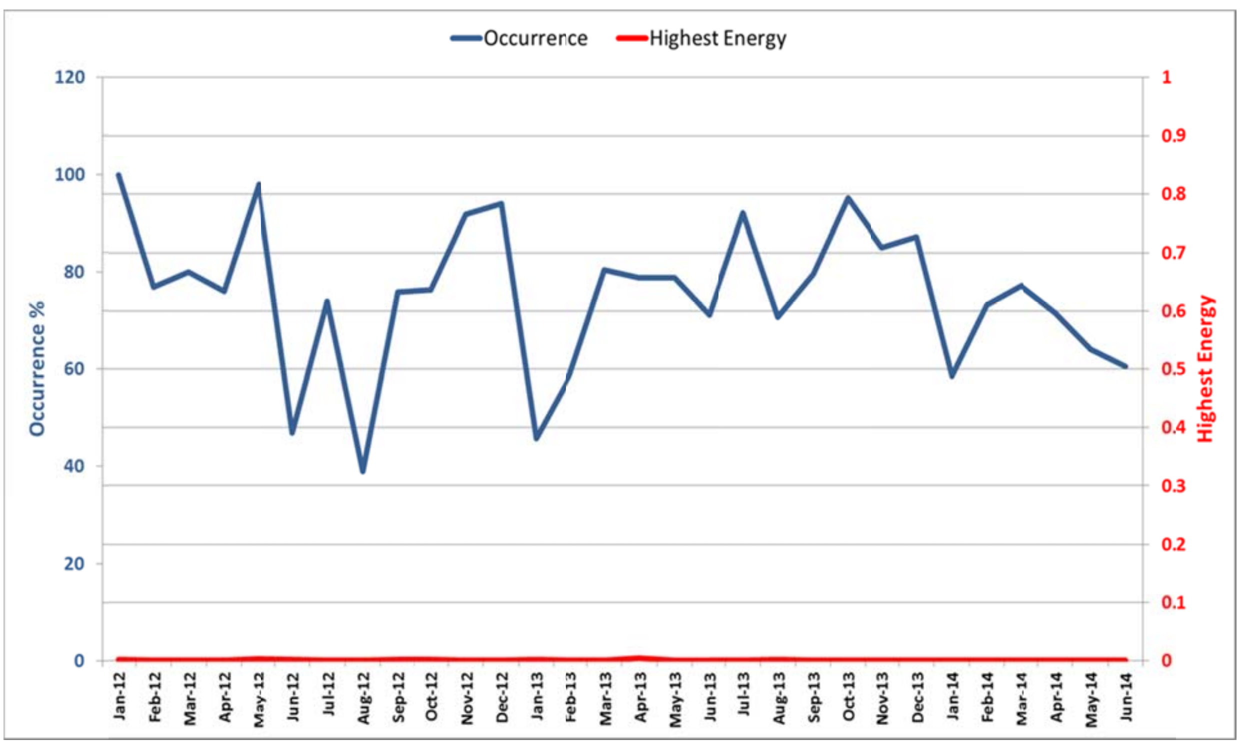

Figure 19. Mode 9 @ Longshore – Mode Occurrence vs. Highest Energy

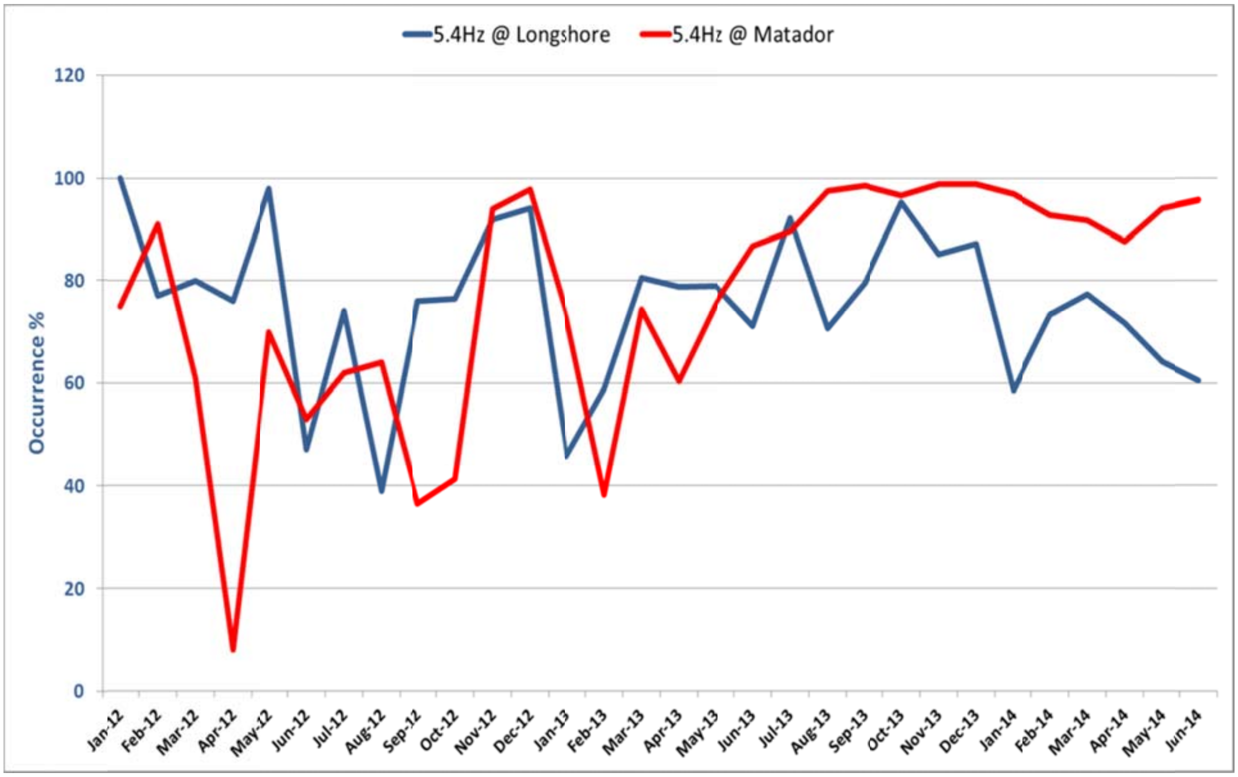

Figure 20. Mode 9 – Matador vs. Longshore

Mode 10: 6.0Hz

Similar to the 5.0Hz & 5.4Hz modes, the study discovered another mode at 6.0Hz, and which was present at six locations, as shown in Figure 21. The mode was strongest at Matador. Figure 22 shows the first indication that the mode at 6.0Hz appears not to be related to average monthly north wind production. But these oscillations are detected more strongly near wind generators. Figure 23 shows the comparison of the mode occurrence with the highest energy level of the current magnitude signal measurement at Matador. The monthly highest energy trend remained fairly flat at low levels (< 0.01) except in Jan-March & August 2012, suggesting that these oscillations are driven by control systems at the local wind generators and can reach high energy levels. This also suggests the need for additional monitoring. The Matador current magnitude signal was selected as the critical location to monitor in real-time.

It is recommended that ERCOT review the 6.0Hz oscillation with wind owners for possible mitigation and also monitor this mode in real time with the following configuration to detect increasing energy levels during high wind production.

- PMU Signal: Matador Current Magnitude.
- Minimum Frequency = 5.5Hz.

- Maximum Frequency = 6.5Hz.
- Minimum Energy = 5.
- Damping = 8%.

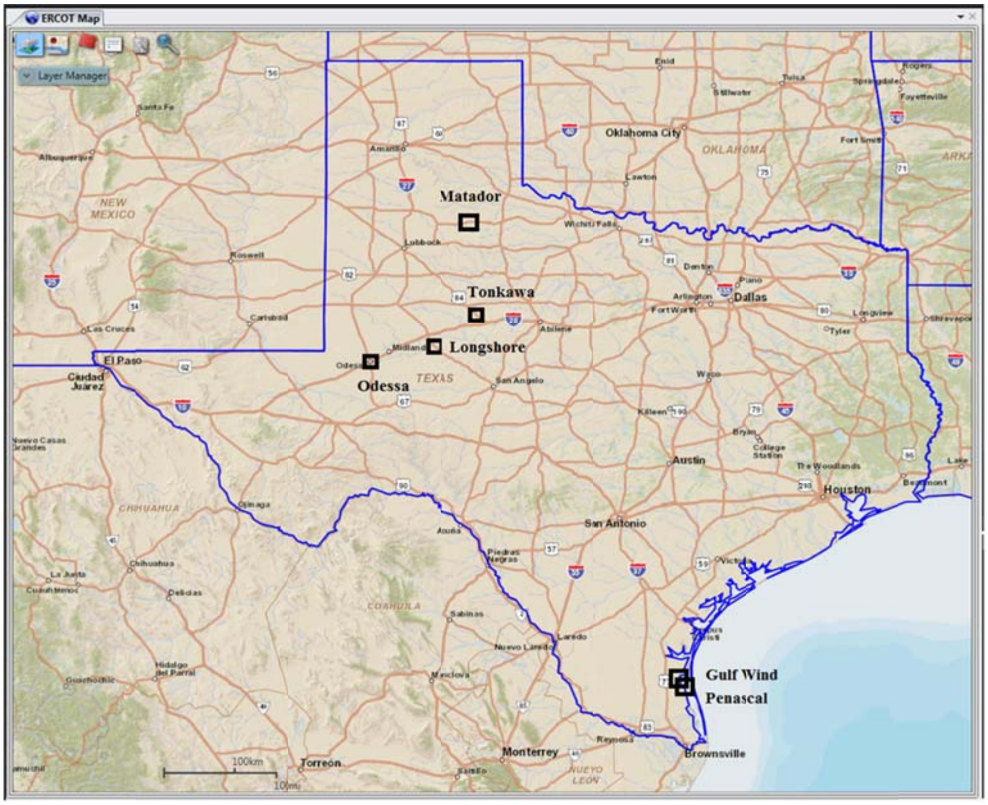

Figure 21. Mode 10 – PMU Location

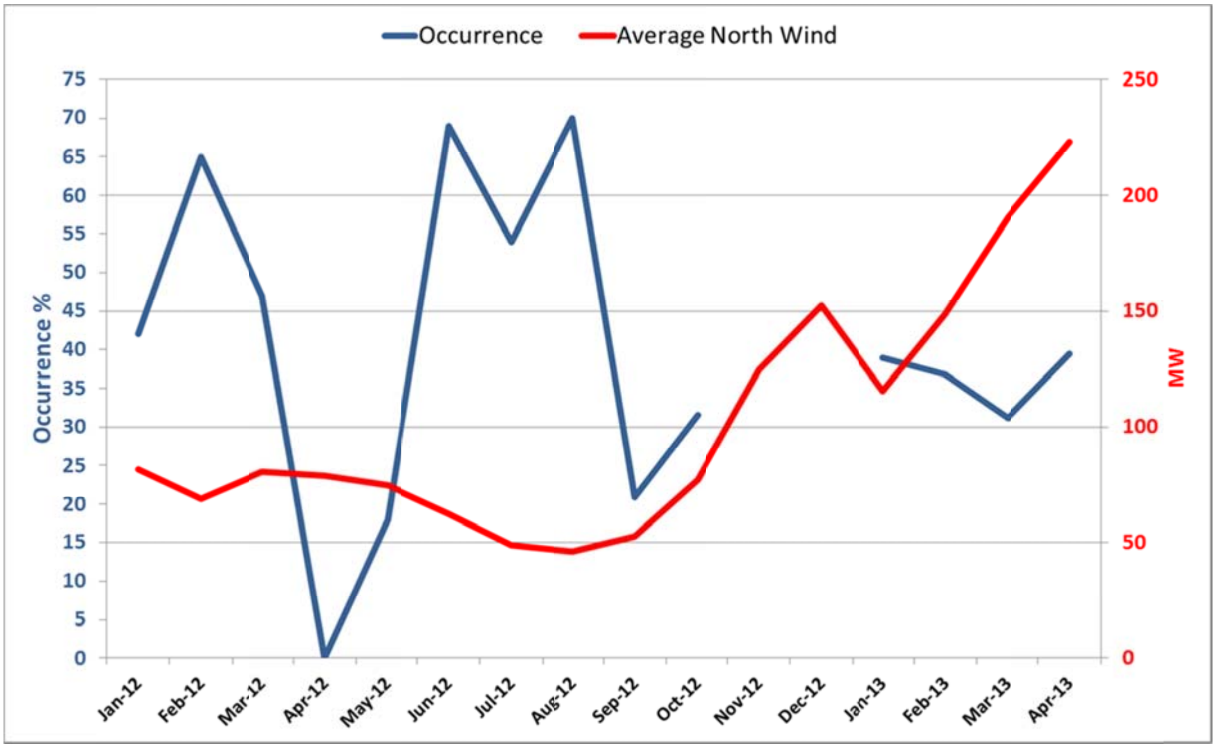

Figure 22. Mode 10 – Mode Occurrence vs. Regional North Wind

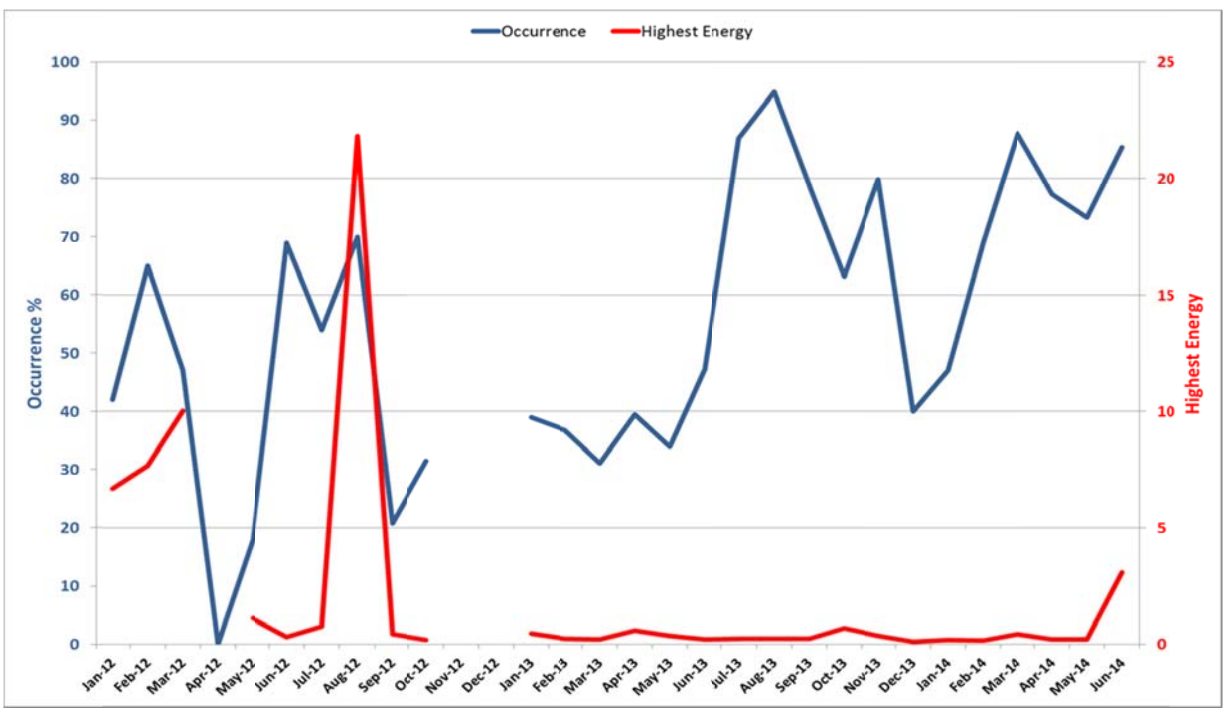

Figure 23. Mode 10 – Mode Occurrence vs. Highest Energy

Matador appears to have two strong modes at 6.0Hz & 5.4Hz driven by the control systems of the nearby wind generators. Figure 24 shows the mode occurrence of 5.4Hz at Matador measured from current magnitude signal spanning 3-years. The mode occurrence at 5.4Hz shows consistently higher persistence than the 6.0Hz trend, but never showed the high energy levels which were recorded for the 6.0Hz mode.

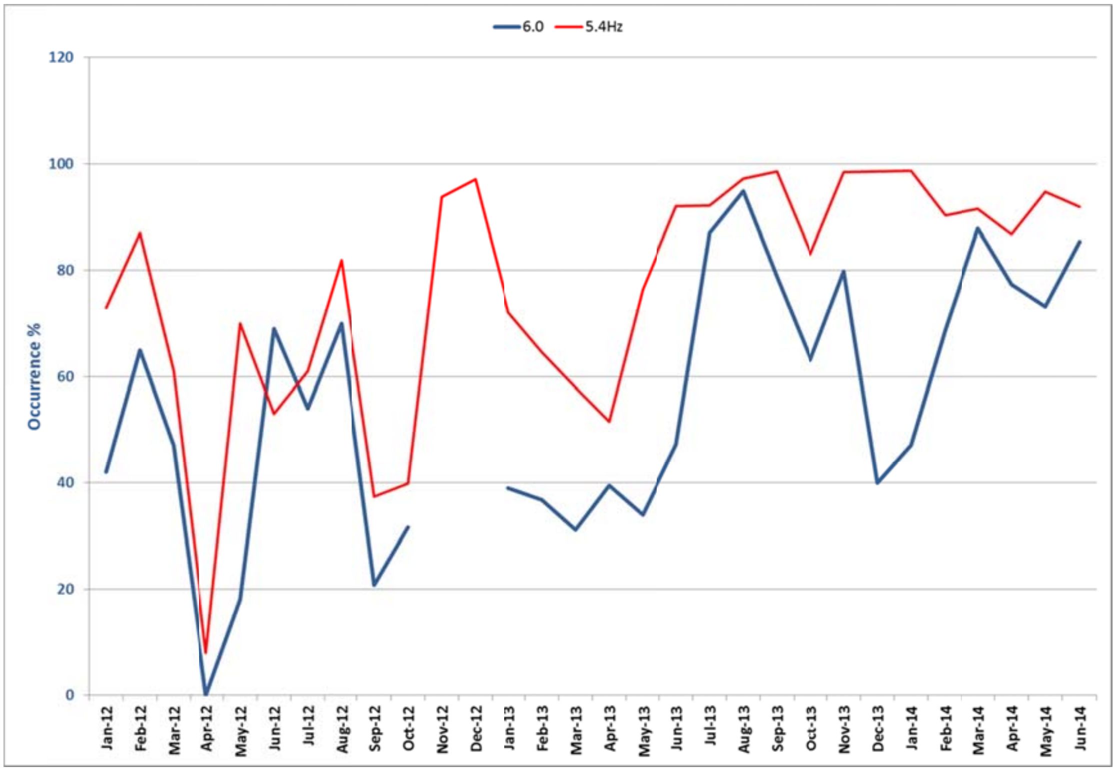

Figure 24. Mode 10 @ Matador – 5.4Hz vs. 6.0Hz

<u>Mode 7: 3.2Hz</u>

Figure 25 shows the PMU location in the ERCOT interconnection that had observed 3.2Hz mode. This mode showed up in the current magnitude signal measurement in the Matador substation. Figure 27 shows the trend of the 3.2Hz mode occurrence in the Matador current magnitude signal over 3-years. The mode does not appear to be consistent such as 5.0Hz, 5.4Hz & 6.0Hz, but rather intermittent. The mode appeared in January, February, March, and June of 2012, then disappeared until January 2014, when it reappeared. The maximum occurrence of 3.2Hz mode appeared for 20% of time in January 2014 and minimum occurrence of the same mode appeared 10% of time in March 2013. Figure 26 shows the comparison between Mode occurrence of 3.2Hz and the monthly average north wind production in MW from January 2012 to April 2013, suggesting no causal relationship

Figure 27 also shows the comparison of the monthly mode occurrence and the highest energy levels, suggesting that the energy of the mode is relatively high when it occurs. This mode appears to be driven by control system setting changes and not to the level of wind production. This mode does not appear all the time with low energy, but rather occurs sporadically with high energy, which requires additional monitoring to detect and mitigate oscillations.

It is recommended that ERCOT do additional monitoring in real-time with the following configuration to detect increasing energy levels during high wind production.

- PMU Signal: Matador Current Magnitude.
- Minimum Frequency = 2.6Hz.
- Maximum Frequency = 3.8Hz.
- Minimum Energy = 50.
- Damping = 8%.

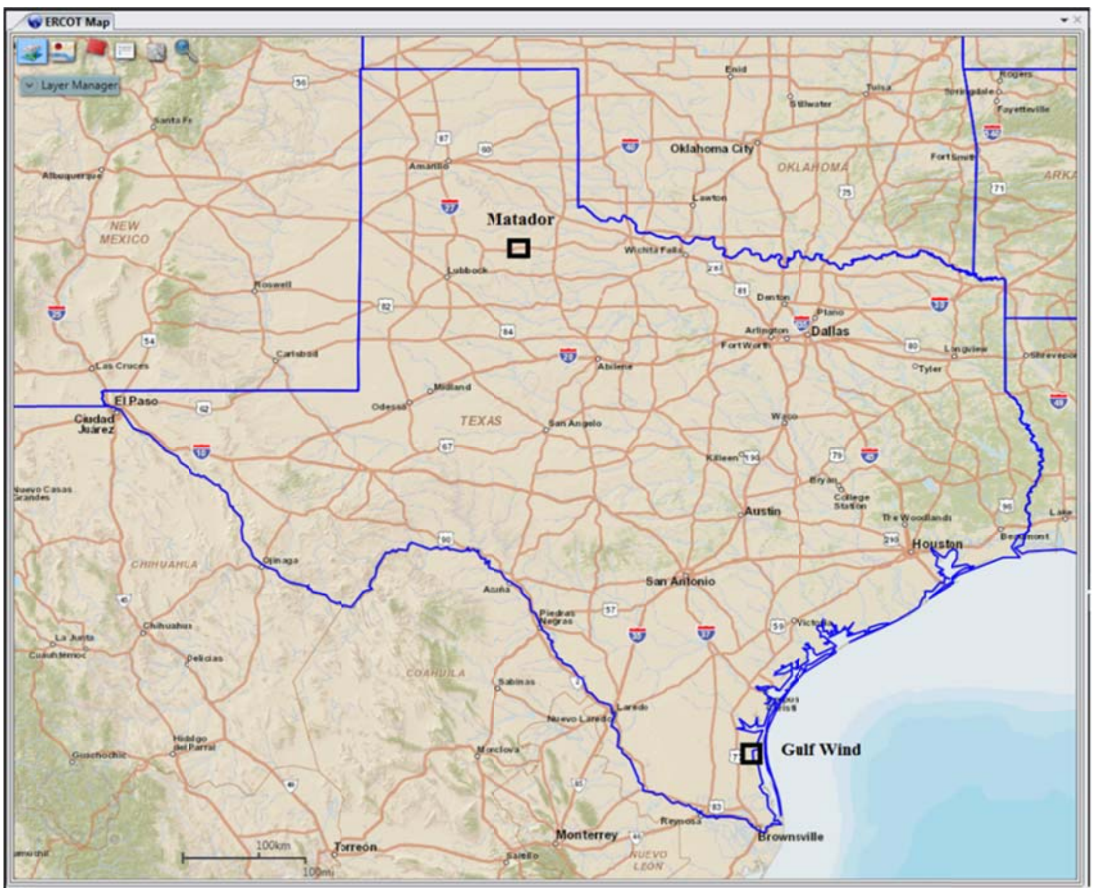

Figure 25. Mode 7 – PMU Locations

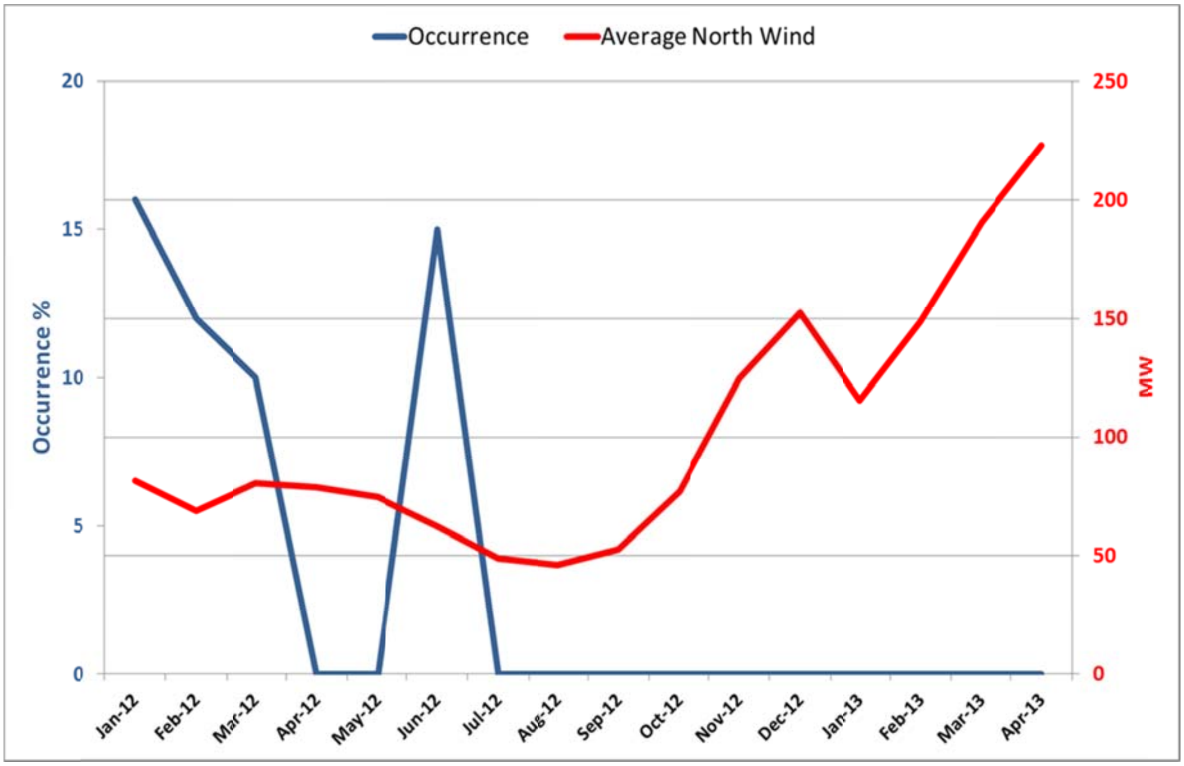

Figure 26. Mode 7 – Mode Occurrence vs. Regional North Wind

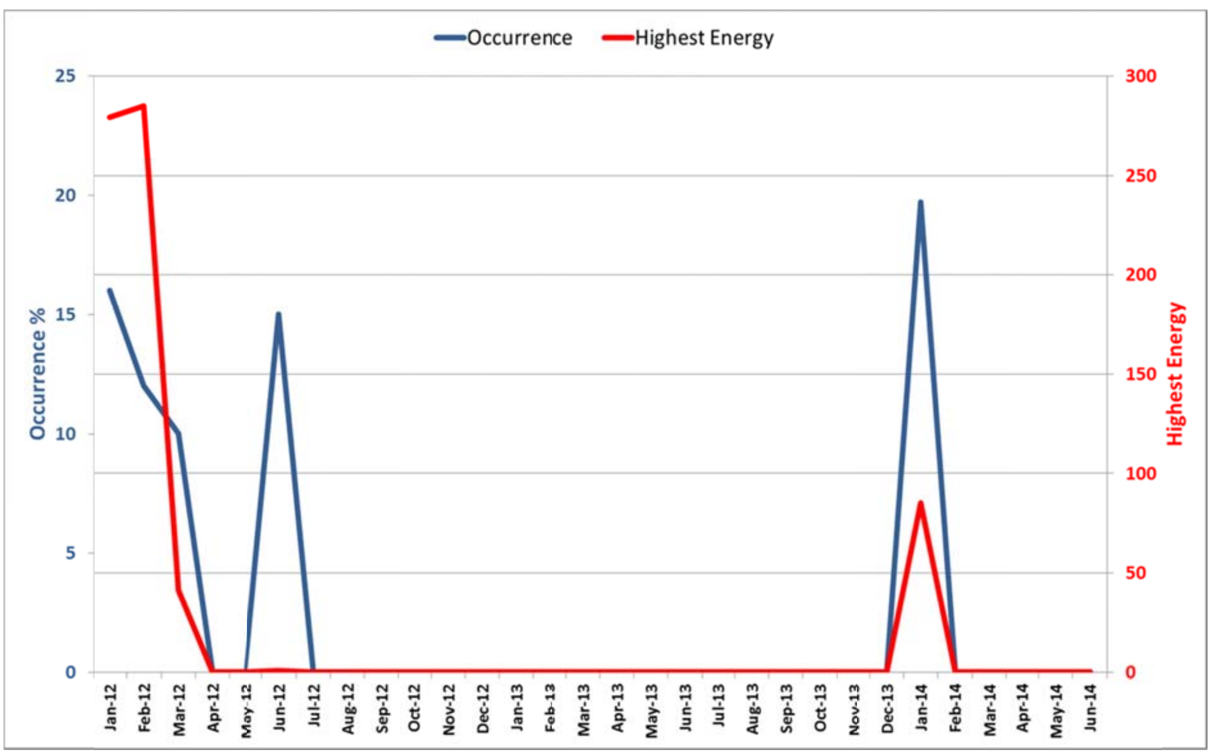

Figure 27. Mode 7 – Mode Occurrence vs. Highest Energy Level

The study also discovered other modes (1.5Hz, 1.7Hz & 2Hz) similar to 3.2Hz which are apparently driven by setting changes in the control systems of the nearby wind generators. The sources and energy levels of those modes are explained below.

Mode 3: 1.5Hz

The study discovered a mode at 1.5Hz at Gulf Wind in the Valley region as shown inFigure 28. This mode occurred only in April 2012 for 0.04% of time, and with a small energy of approximately 0.02. Figure 29 shows the comparison of the mode occurrence at Gulf Wind current magnitude signal with the average south wind production, suggesting that this mode occurs intermittently and is driven by settings change in the wind generation control systems. It is recommended that ERCOT do additional monitoring of this mode with the following configuration.

- Minimum Frequency = 1.0Hz.
- Maximum Frequency = 2.0Hz.
- Minimum Energy = 0.1.

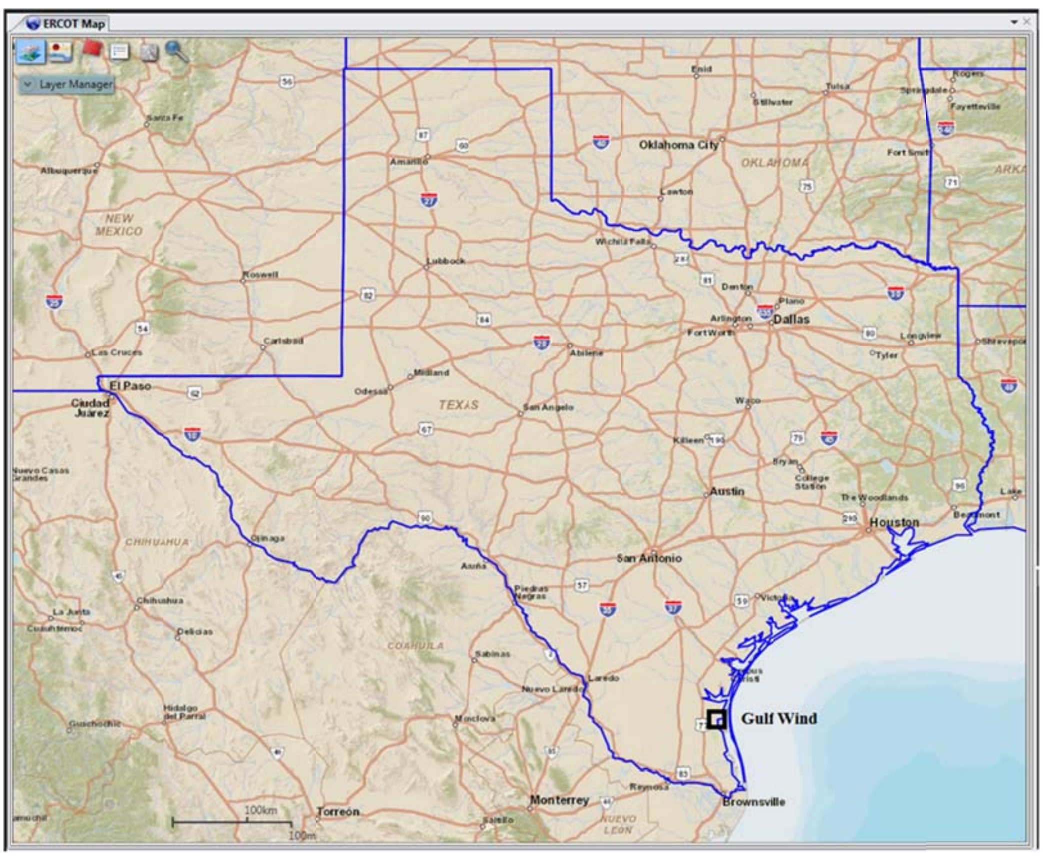

Figure 28. Mode 3 – PMU Location

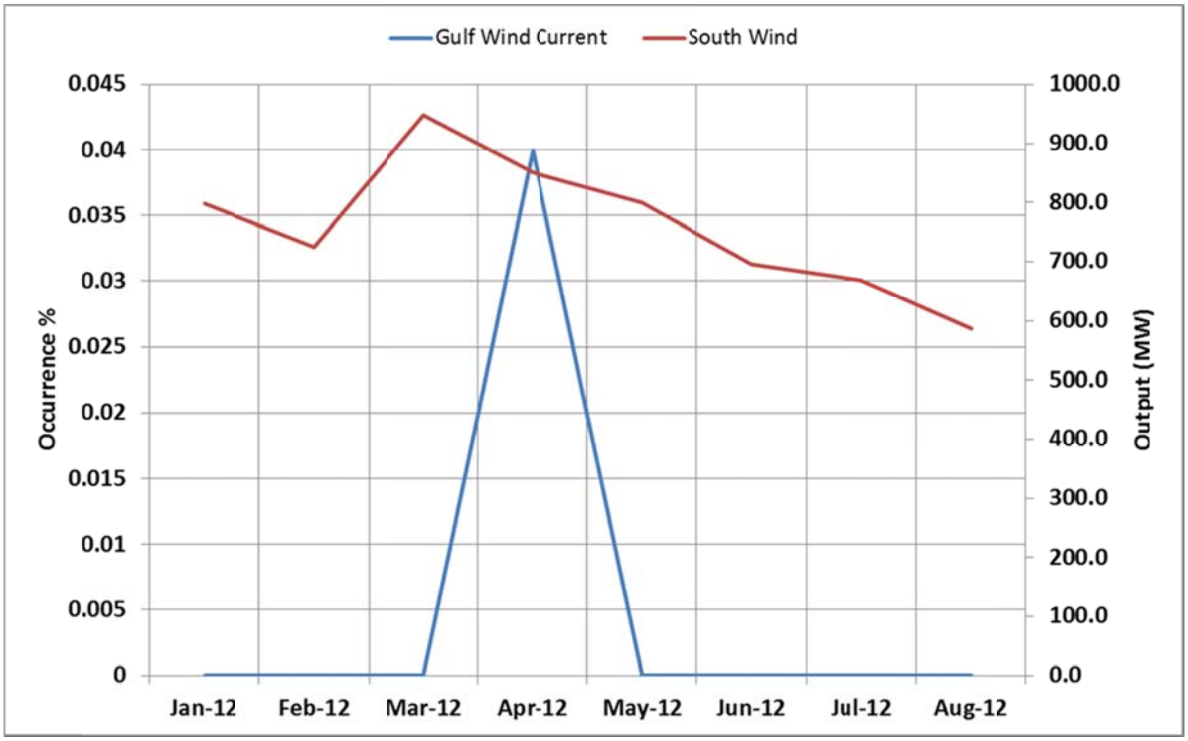

Figure 29. Mode 3 – Mode Occurrence vs. Regional South Wind

Mode 4: 1.7Hz

The study also discovered a mode at 1.7Hz at Odessa in West Texas region as shown inFigure 30. This mode occurred only in January 2012 for 4% of time with high energy of approximately 36. Figure 31shows the comparison of the mode occurrence at Odessa in the current magnitude signal with the average west wind production, suggesting this is an intermittent occurrence. The oscillation was observed more strongly near Odessa, which has nearby Combined Cycle Units in Ector County. This appears to be a local issue & ERCOT needs to review the appearance of this mode with the local generation plant owners to determine the root cause, and to evaluate the need for additional monitoring.

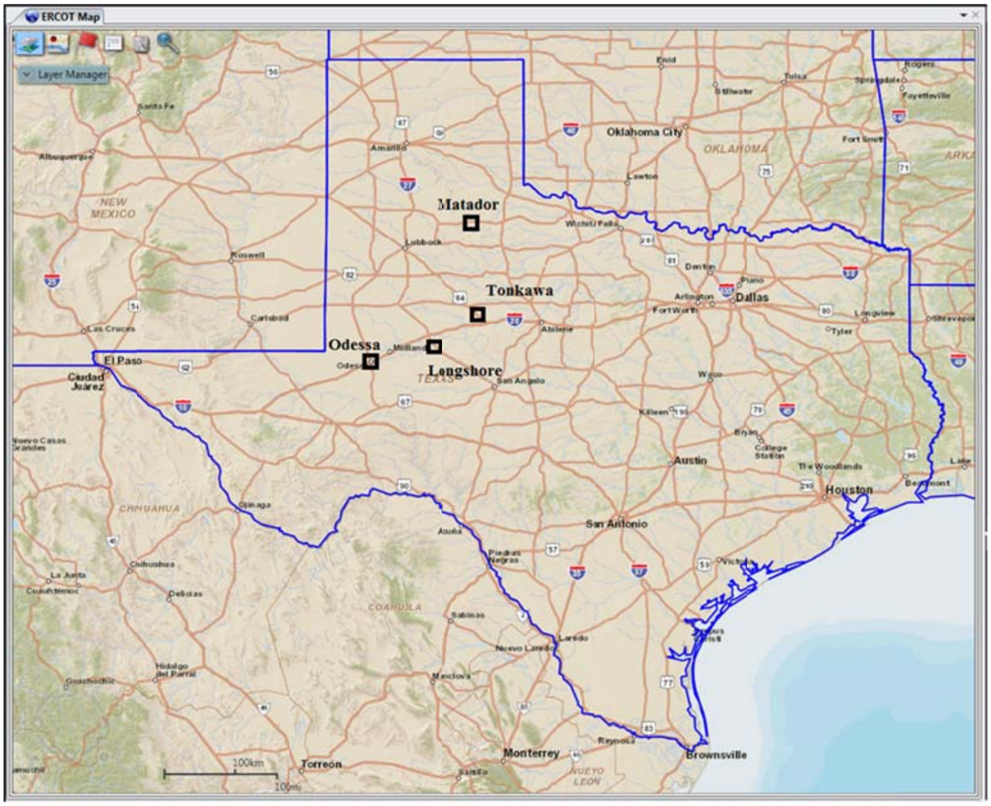

Figure 30. Mode 4 – PMU Location

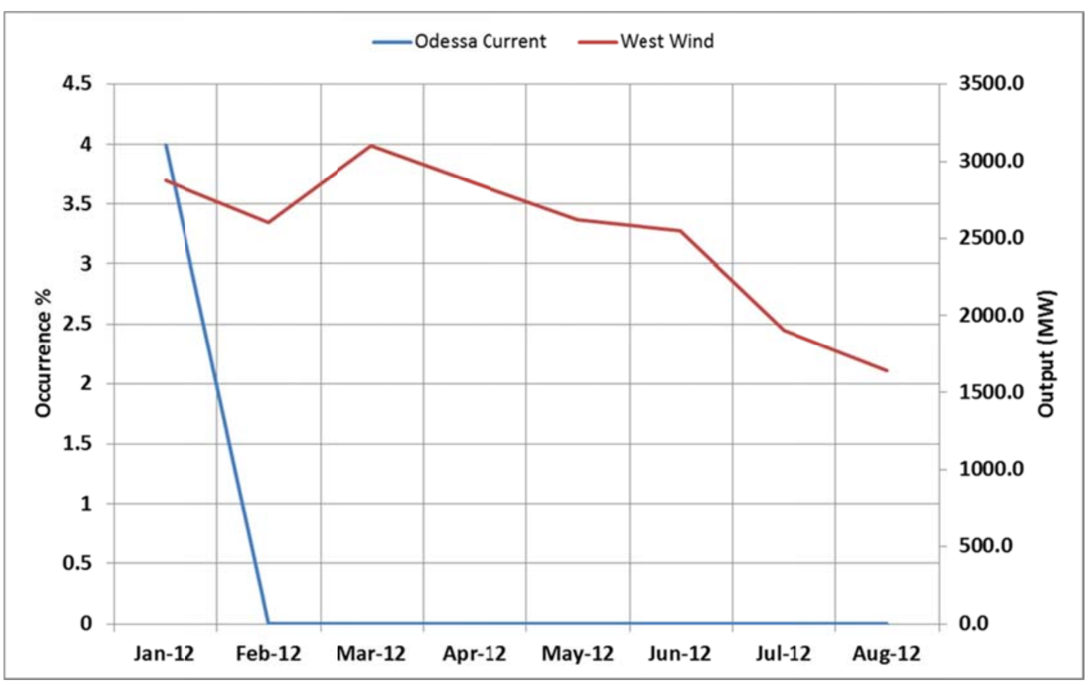

Figure 31. Mode 4 – Mode Occurrence vs. Regional West Wind

Mode 5: 2.0Hz

The study also discovered another mode at 2.0Hz at Gulf Wind (Voltage Magnitude Signal measurement) in Valley region as shown in Figure 32. This mode occurred only in April 2013 for 0.8% of time with high energy approximately 0.5. The oscillation was observed more strongly near Gulf Wind, having nearby wind generators such as Gulf Wind, Penascal & Red Fish. It is recommended that ERCOT do additional monitoring of the mode with the following configuration.

- Minimum Frequency = 1.5Hz.
- Maximum Frequency = 2.5Hz.
- Minimum Energy = 0.1.

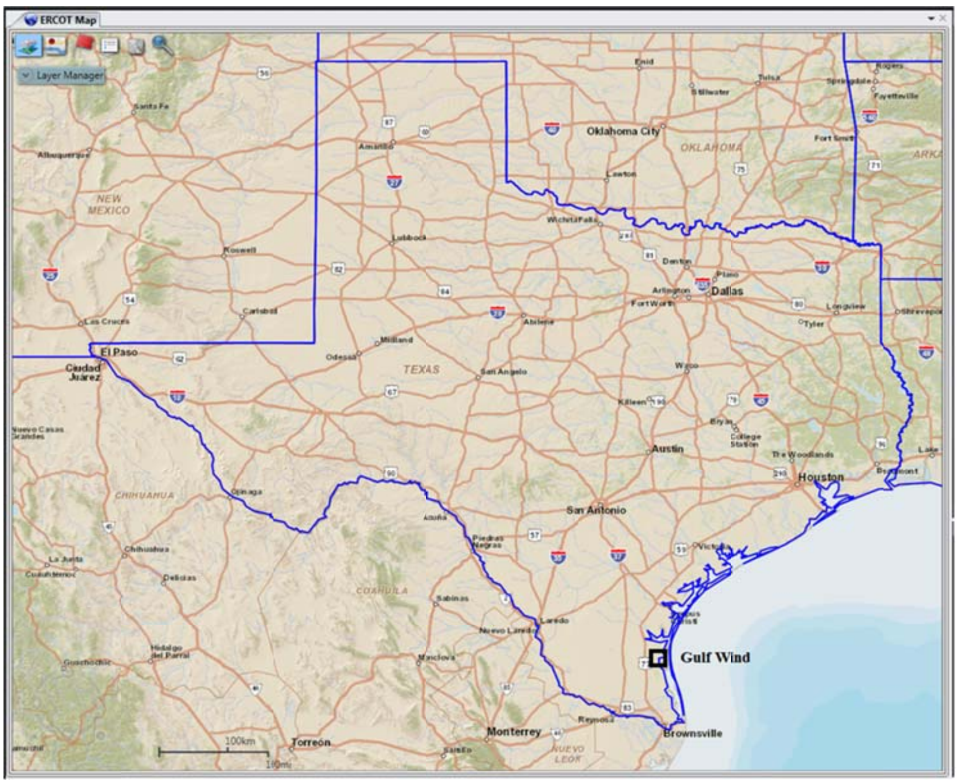

Figure 32. Mode 5 – PMU Location

Mode 1: 0.6Hz

The study discovered a mode at 0.6Hz, showing most strongly in the Matador current magnitude signal, and which appeared for the first three months of 2012 and was never detected again. This mode occurrence at Matador did not follow the average north wind production but was observed at nearby wind generators including Whirlwind at Matador. This appears to be a local issue and may be related to a local oscillation triggered by a transmission network topology change. The maximum highest energy of the mode was approximately 2 and minimum highest energy was about 1.6. It is recommended that ERCOT review the appearance of this mode with plant owners in order to determine the root cause, and to evaluate the need for additional monitoring. Figure 33 shows the PMU locations that observed the 0.6Hz mode, but more strongly at Matador. Figure 34 shows the comparison of the mode occurrence with the average monthly north wind production and indicates that it is likely not related to the level of wind production.

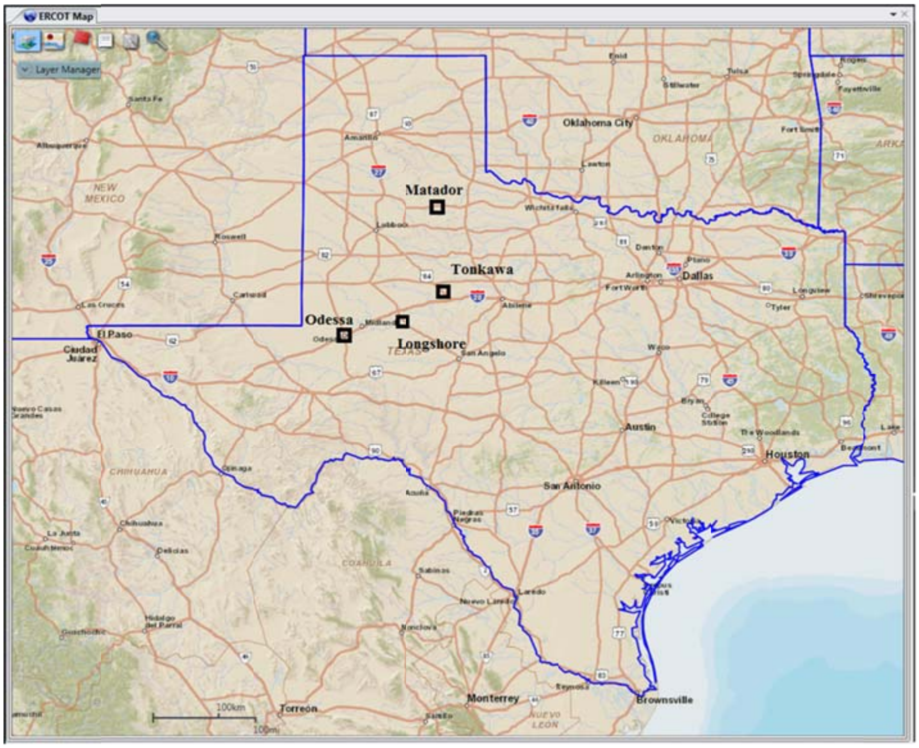

Figure 33. Mode 1 – PMU Location

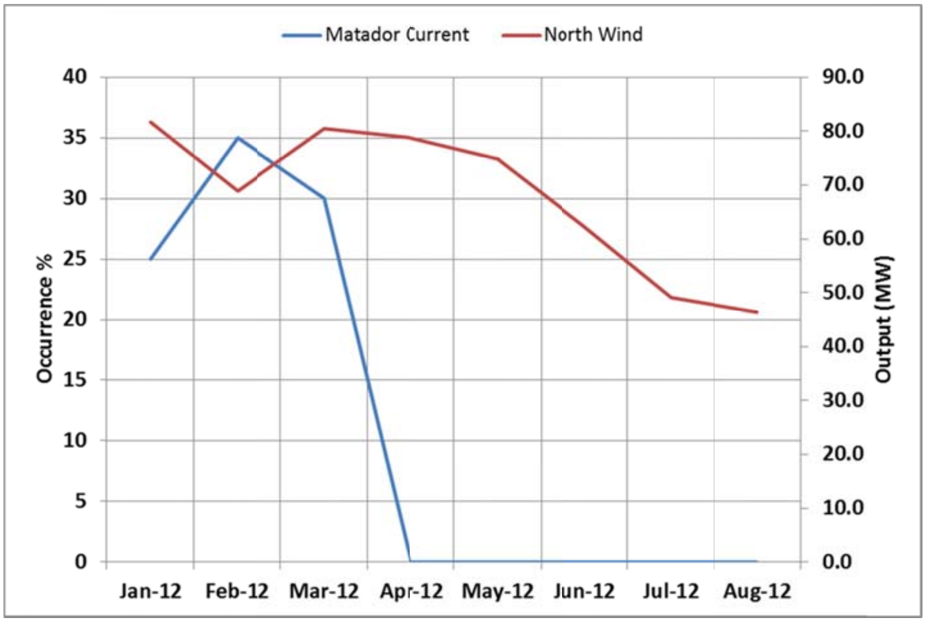

Figure 34. Mode 1 – Mode Occurrence vs. Regional North Wind

10. Conclusion

The detection of unknown oscillations from phasor data spanned 3-years of ERCOT synchrophasor data, and was performed using the Phasor Data Mining Tool. The tool enabled the automatic scanning of the data in periodic intervals, and produced a results summary, including detected oscillations, percentage of occurrence (time), and energy level time-stamped with the PMU location.

This analysis was based on six PMUs located at nearby wind farms in the ERCOT Interconnection. The Phasor Data Mining Tool was configured with the needed algorithm settings to scan for oscillations within the frequency band from 0.1Hz to 15Hz. The measurements including Frequency, Voltage Phasor and Current Magnitude for each PMU were used to scan through the input data for oscillation modes using 60-second blocks of data, and when oscillations were detected, the calculated damping and energy of each mode was recorded. The results were time-stamped and tagged to the PMU measurements to identify the source of the oscillations. The tool was asked to discard modes with damping greater than 8%. The tool leveraged the PMU status information to clean bad data in order to avoid false detections. The output results from the tool were parsed and post processed through MATLAB scripts to rank the oscillatory modes according to high occurrence and high energy. Then the results were studied to identify any relationships between Mode Occurrence and Regional wind data. The highest energy of each mode was extracted and compared with the Mode Occurrence to baseline the minimum energy required to monitor the mode in real-time, and also to differentiate modes related to wind production versus modes driven by control systems or setting change in control systems.

Some of the key findings are as follows:

1. The Study identified 10 different ERCOT Oscillatory Modes.
2. The Occurrence of 2 modes appear to be related to wind production – 0.9Hz (Tonkawa) & 2.7Hz (Longshore).
3. The Occurrence of 4 modes appear to be related to control system settings changes – 1.5Hz (Gulf Wind), 1.7Hz (Odessa), 2Hz (Gulf Wind), 3.2Hz (Matador).
4. The Occurrence of 3 modes appear to be related to the presence of wind generation and control systems - 5.0Hz (Gulf Wind) ,5.4Hz (Matador & Longshore), 6.0Hz (Matador).
5. The Occurrence of 1 mode appears to be a local oscillation due to a topology change or tuning of wind generators – 0.6Hz (Matador).

This study concludes that four modes appear consistently for 3-years and are still present. There are four other modes that appear intermittently with high energy. There are two other modes that appeared consistently at the beginning of the study, and then were never detected again. The report provides insights on the configuration for monitoring certain modes in real-time to detect these oscillations. The modes which disappeared after some duration of time may need additional review by ERCOT with plant owners to determine the root cause and to evaluate the need for additional monitoring.

11. Appendix

1. Final Report Presentation Material - "CCET_Data_Mining_Oscillation_Study_313b_110414".
2. "Wind Oscillation Study – Monthly Statistics" Excel Spreadsheet