

Wide-area Situational Awareness Application Developments

A Dissertation Presented for
the Doctor of Philosophy
Degree

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DEDICATION

I dedicate this dissertation to my parents Jianguo Ye, Huiying Lin, and my husband Qian Li for their endless love, and encouragement through my life.

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ABSTRACT

This dissertation expands the topics from the wide-area situational awareness application development, system architecture design, to power system disturbance analysis. All the works are grounded on the wide-area Frequency Monitoring Network (FNET). The FNET system takes GPS-synchronized wide-area measurements in a low-cost, easily deployable manner at 120V single-phase power outlet. These synchronized observations across the entire system enables the monitoring of bulk power systems, and provides critical information for understanding power system disturbances and system operations.

Firstly, the work addresses the viability of angle measurement to serve different types of situational awareness applications. The first is the viability of angle measurement for identifying the disturbance locations instead of original frequency-based methods. A set of approaches are proposed to collectively serve the purpose of estimating disturbance locations for generation trip or load shedding events in power system. There are two major methods being proposed in this work: TDOA-based event location triangulation and oscillation-based event location estimation. The second is the viability of angle data to serve the real-time power system visualization. A real-time angle visualization framework is proposed and implemented to interpret the real-time FNET angle measurement and provide the system awareness in an intuitive way. The framework covers the basic functions including real-time angle contour map display, recording and playback for recent time window.

As another part of this dissertation – system architecture design, a sound FNET power system event monitoring and automatic event reporting system is constructed and enhanced with NERC Frequency Response Initiative (FRI) tasks included to improve power system situational awareness capability. The system aims at effective multi-thread event detection in

different synchronous power systems, flexible event recording, on-line event analysis, on-time event alerting, etc.

The dissertation also covers the work on power system disturbance analysis (Chapter 5-Chapter 7). As first, the statistical characteristics of frequency disturbances captured by FNET system are analyzed and compared across different interconnections in NA power grid from 2008 to 2011. And with the FDR deployment in some other worldwide countries beside NA, e.g. Europe, China, etc, typical frequency response characteristics of the generation and load loss events in these areas are also analyzed, and compared with NA power grid. Secondly, some major disturbances in NA power grid from 2010 to 2011 are investigated using FNET angle, frequency and voltage measurements. In the final part, the inter-area oscillation modal analysis is performed on different types of frequency disturbances in WECC, which helps to provide a geographical view of the inter-area mode distributions in Western Interconnection.

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Chapter 1. Frequency Monitoring Network (FNET)

1.1. FNET Framework

The Frequency Monitoring Network (FNET) is a wide-area phasor measurement network at the 120V distribution voltage level, first built in 2004 at Virginia Tech and operated in University of Tennessee since late 2009. The FNET system consists of a large number of GPS-time synchronized Frequency Disturbance Recorders (FDRs) distributed across the North America and worldwide areas as well as a data collection and processing center. The information obtained from the FNET makes it possible for various situational awareness applications [5]-[11], e.g. frequency event detection, oscillation detection, real-time visualization, etc. The FNET system has served utilities, academics, and policy makers with valuable synchrophasor data from North America power grid.

Up to Sept 2011, nearly 100 FDR units have been deployed covering the four North American Interconnections: Eastern Interconnection (EI), Western Electricity Coordinating Council system (WECC), and Electric Reliability Council of Texas system (ERCOT) and Hydro Quebec area, and even some other worldwide countries (Europe, China, Korea, etc). Fig. 1-1 shows the FDR deployment across NA power grid. With the increasing cooperation with utilities, ISO, universities and research labs, there will be more intense deployment of FDRs in the near future.



Fig. 1-1. Map of FDR deployment in North America

Fig. 1-2 demonstrates the framework of FNET system. Phasor measurements from the North America and worldwide power grids are collected by widely installed FDRs, and are transmitted via the Internet to a local client or remote data center hosted in FNET labs. In most of the cases, FDR data are transmitted to the FNET data center for real-time data processing and long-term data storage. In order to understand the uniqueness and advantage of the FNET system, there are two major parts worth being introduced specifically. One is FDRs, which perform local GPS synchronized measurements and send data through the Internet; the other is the FNET data center, which includes data collection/storage server, application server, web server and backup servers, etc.

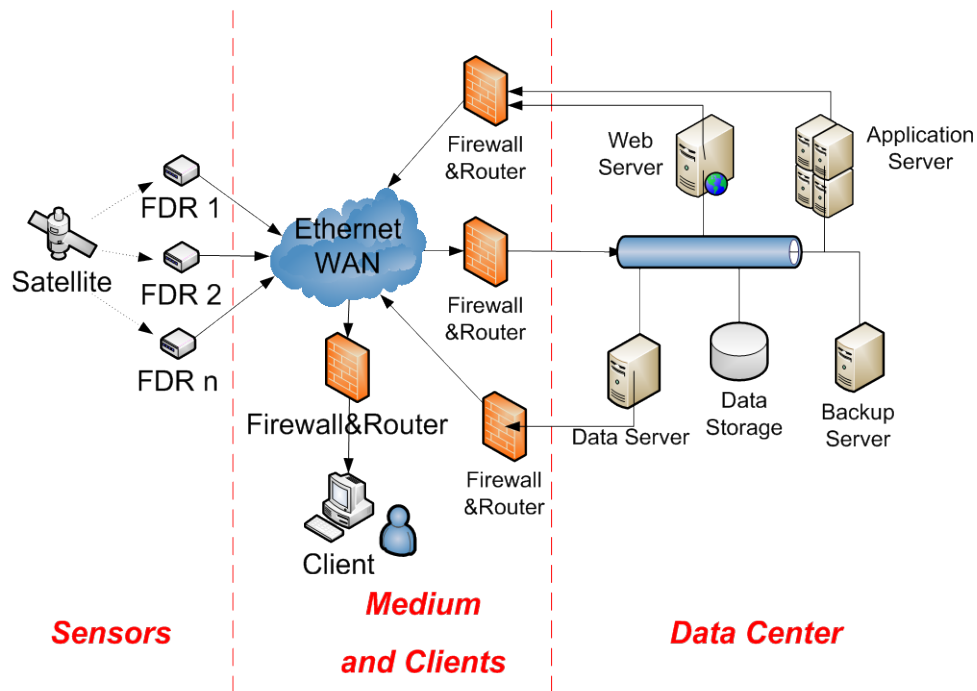


Fig. 1-2. The Framework of Frequency Monitoring Network (FNET) system

1.1.1 Frequency Disturbance Recorder

The measurement sensors used in Frequency Monitoring Network (FNET) are referred to as Frequency Disturbance Recorders (FDR). Each FDR in the network measures the voltage magnitude, phasor angle, and frequency from the 110 V outlet (220 V for sensors placed in Europe) into which it is connected. A GPS timestamp is then attached to the measured quantities and sent via the Internet to the information management server (IMS) maintained in FNET labs. The FDR is able to output the measurement with sub-second resolution (10 samples per second) and high accuracy [3][4]. As we will see in the following chapters, sub-

second measurements actually provide a wealth of knowledge regarding the health and dynamics of the electric grid.

1.1.2 Data Center

The FNET data center plays a critical role in the entire FNET system framework. All the FDR measurement data are concentrated and processed here. Physically the FNET data center is operated on several dedicated servers, e.g. data server, application server, web server, backup server, etc. Functionally, the data center can be treated as a multi-layer data management system as shown in Fig. 1-3.

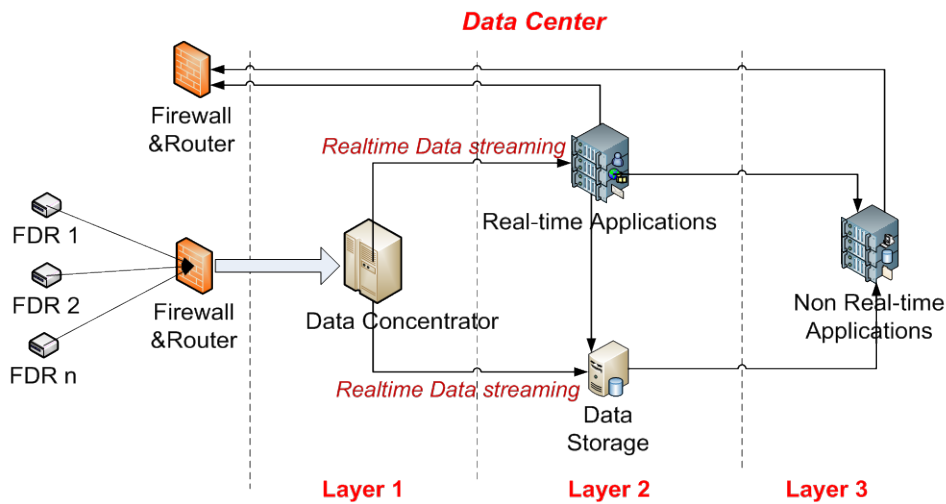


Fig. 1-3. Hierarchical Structure of FNET Data center

The top layer is the FNET data concentrator, which can be seen as the intermediate interface between the FDRs and other layers in FNET system. The data communication between all active FDRs and this interface is based on TCP/IP protocols. In the data concentrator, the FDR measurement is extracted from network data package, interpreted, error checked, time-aligned, and then streamed into different layers for real-time applications or data storage.

The second layer of the data center hierarchy is composed of the real-time application agent and the data storage agent. The real-time application agent is composed of various real-time applications, e.g. the frequency monitoring interface, frequency event detection, and oscillation detection, etc. The function of the data storage agent is to simply receive and store all the FDR record for permanent data archival.

The third layer is non real-time application agent. Applications implemented on this layer are operated on various saved data format (e.g. txt, MySQL data) instead of real-time streaming data, e.g. event visualization application, frequency event analysis, oscillation modal analysis, oscillation pattern recognition, and web services.

1.2. Organization of Study

Chapter 2 explores the viability of using FNET angle measurement for identifying the event location instead of using frequency measurements. A set of approaches are proposed to collectively serve the purpose of estimating the event location for generation trip or load shedding events in power system. Two main methods are named: TDOA-based event location triangulation and oscillation-based event location estimation. And these methods are evaluated with historical power system frequency disturbances. These events have confirmed actual event locations. The offline testing proves the effectiveness of the angle-based location method.

Chapter 3 addresses the FNET event monitoring and automatic event reporting system with NERC Frequency Response Initiative (FRI) enhancements. The enhanced system framework and some necessary components are introduced, e.g. the multi-thread event trigger mechanism, flexible event recording design, FRC (frequency response characteristic) calculation module, etc.

Chapter 4 proposes a real-time angle visualization framework, which aims to provide a real-time view of the power system operation with FNET wide-area angle measurement for system operators. The real-time angle measurement is streamed into the visualization framework, then after data conditioning and angle data calibration, the VTK-based visualization module will automatically generate angle contour map for EI system and angle playback movie. The real-time angle contour map and playback animation movie is accessible through FNET web services.

Chapter 5 investigates the statistical characteristics of frequency disturbances in NA power and Europe power grids with FNET-captured events. For the NA power grid, the statistical characteristics of frequency disturbances are analyzed and compared in Eastern and Western Interconnections from 2008 to 2011. The comparisons are made on the disturbance occurrences during a day, a year, a week. The yearly trend is also compared. For the other worldwide power grids, typical frequency response characteristics of the generation and load-loss events are analyzed, and compared with NA power grid.

Chapter 6 continues the discussion of power system disturbances by analyzing several major events in North America power system in 2010 and 2011. Frequency, voltage and phase angle measurements are examined to understand the dynamic signatures of these disturbances. These major events include a HVDC line trip in Hydro-Quebec and New England area, a large generation drop in WECC involving the Pacific HVDC outage, an islanding event in WECC, a large load drop disturbance causing the blackout in Toronto area, a multi-disturbance event that involves line trips and multi-unit generator trip in EI, and the Southwest Blackout.

Chapter 7 focuses on the oscillation modal analysis in Western Interconnection, using FNET angle measurement. The Matrix Pencil tool is applied on the oscillatory angle measurement of different types of disturbances in Western Interconnection.

Chapter 8 concludes the dissertation and proposes the future work.

Chapter 2. Power System Disturbance Location Estimation

The Frequency Disturbance Recorders (FDRs) measure frequency, phase angle and voltage magnitude from single-phase voltage waveform at any 120 V outlets. The measurement data are continuously transmitted via Internet to the FNET servers. These measurements can tell volumes about the power system operation status. There are a number of applications associated with power system situational awareness in FNET system, among which three critical modules usually cooperate with each other for frequency disturbance monitoring and analysis, which are event detection, event amount estimation, and event location estimation. This chapter will firstly introduce the first two modules briefly, and then the chapter will mainly focus on the development of new event location estimation methods.

The manner in which frequency perturbations travel throughout the power grid has been extensively studied in the past [12]. Such perturbations are known to propagate throughout the grid as a function of time and space [13]. The dynamic information hidden in the frequency measurement, which is called wave front arrival time or Time Delay of Arrival (TDOA), has been well used for event location estimation and applied on FNET system since 2006 [10].

However, the voltage phase angles taken at different locations in a power system are also effective in monitoring the state of the power system. It has been recognized that phasor are applicable even when the waveforms are changing rather rapidly and contain significant amounts of transient components [18]. The goal of this research is to formulate a practical and efficient event location algorithm using phasor angle data instead of frequency measurements, to extend the disturbance location estimation to a broader dimensionality.

2.1. Event Detection

Any disturbance that leads to a large or sudden mismatch of active power will cause a significant frequency variation [9][10]. The FNET application server has implemented an online event detection module utilizing dynamic frequency variation since 2006, which is capable of indentifying generation trip-like or load shedding-like disturbance [8].

The FNET event detection module detects such phenomena by continuously monitoring the incoming FDR frequency data as it arrives at the data center. The event detection module uses rate of average frequency change (df/dt) as an indicator of power system disturbance. If

the rate of frequency change exceeds a pre-defined threshold, the disturbance detection will be triggered. And a voting mechanism is further introduced to avoid false alarming caused by abnormal outliers from some FDR units. The thresholds for event detection are different in the four interconnections due to their unique frequency response characteristics. In other words, the same amount of generation trip or load loss will cause different rates of change of system frequency. In most cases the thresholds are empirically determined, e.g. 3.3 mHz/sec for Eastern Interconnection, 7 mHz/sec for Western Interconnection.

A chart explaining the rate of frequency change in event detection algorithm is shown in Fig. 2-1. This example assumes the continuous monitoring of two FDRs. However, in general, a trigger can be created using data from n FDRs in the same interconnections. The general detection steps are described as follows:

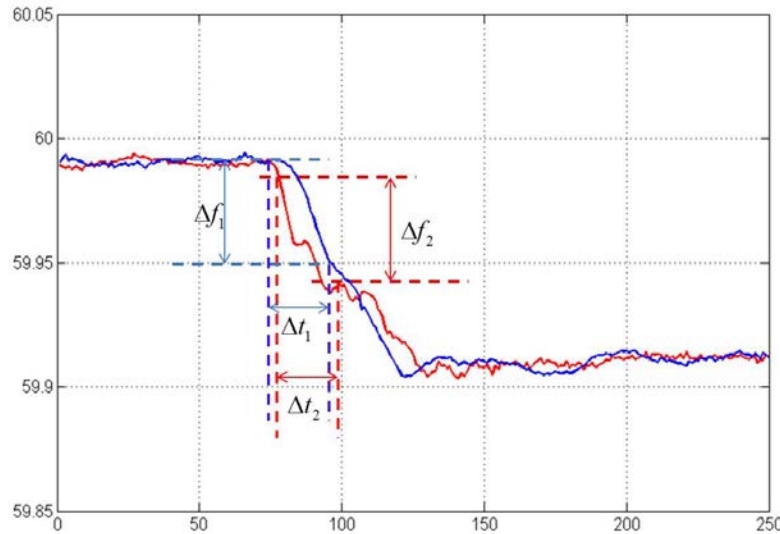
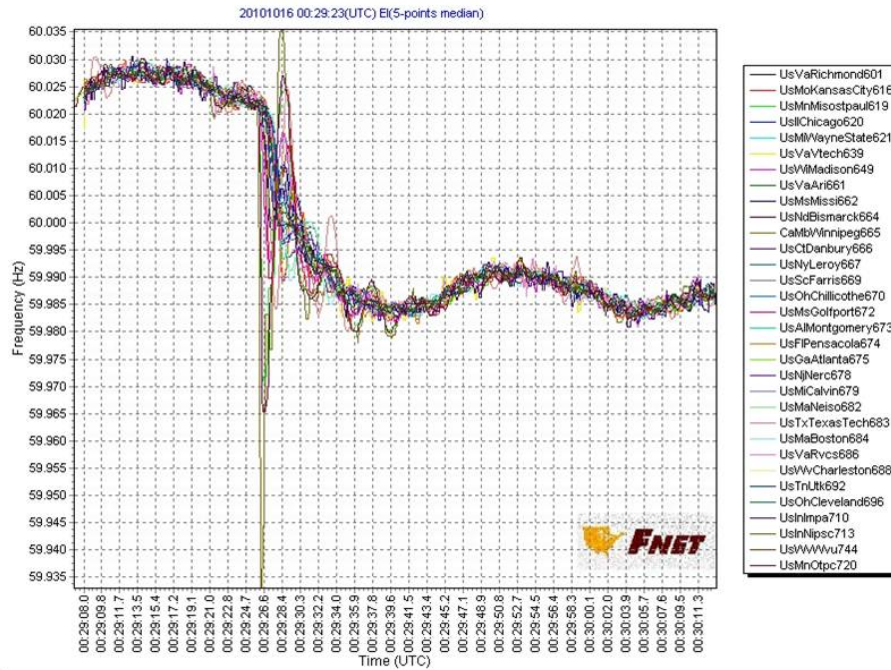


Fig. 2-1. Schematic Diagram of Event Trigger Algorithm

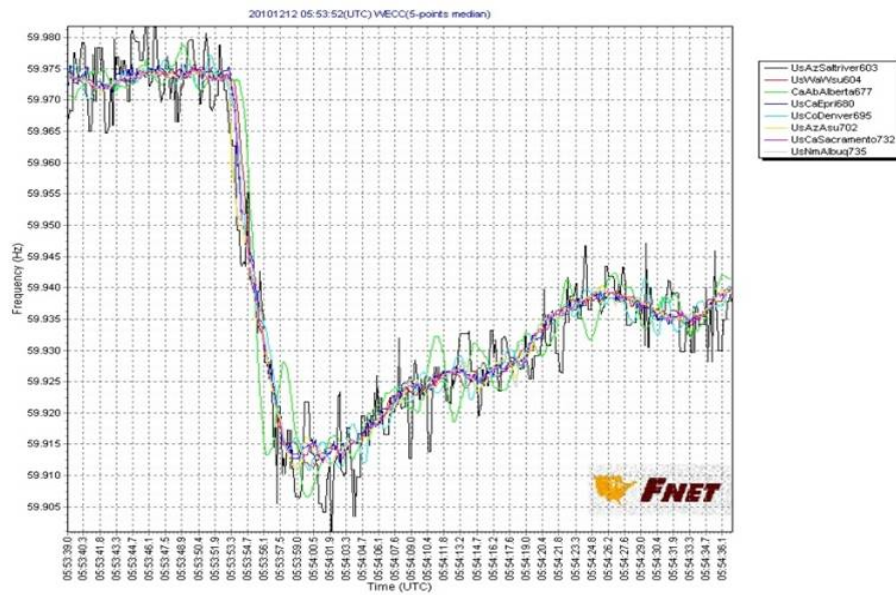
1) Perform data conditioning using median filter or other data smoothing technique to filter out the outliers;

2) Calculate the rate of frequency change $\frac{df_1}{dt_1}, \frac{df_2}{dt_2}, \dots, \frac{df_n}{dt_n}$, if $\left| \frac{df_1}{dt_1} \right|, \left| \frac{df_2}{dt_2} \right|, \dots, \left| \frac{df_n}{dt_n} \right| > threshold$, then a frequency disturbance is claimed.

Fig. 2-2 displays the typical generation trip events in EI, WECC systems. Besides the generation trips, frequency disturbances caused by load shedding could also evoke a positive response from this module. Fig. 2-3 displays a load shedding event in EI.



(a) Generation Trip in EI



(b) Generation Trip in WECC

Fig. 2-2. Examples of generation trip in North America Power Grid

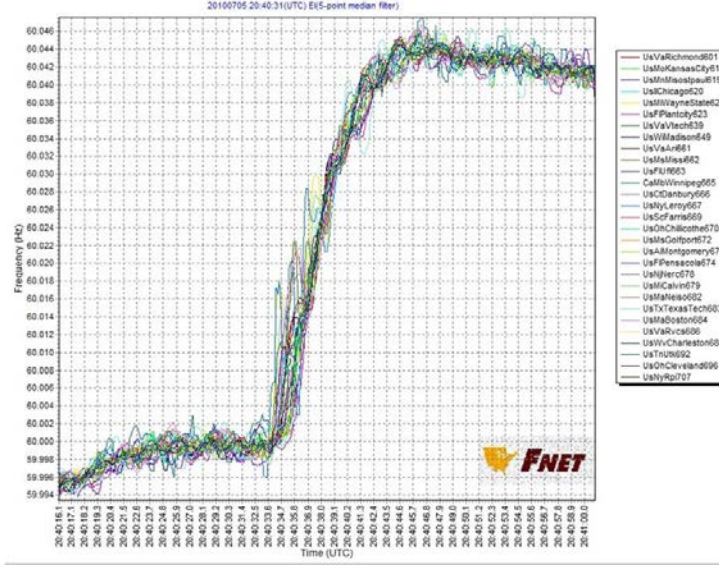


Fig. 2-3. Example of load shedding in EI

2.2. Generation-Load Power Mismatch Estimation

Once a frequency event is detected, a rough power mismatch during events can be estimated. If the average frequency deviation before and after the event is represented as Δf , the frequency change Δf is related to the system active power mismatch during the event, which is generally referred to as β (frequency response characteristic) [16][17], then

$$\Delta P = \beta \Delta f \quad \text{Eq. 2-1}$$

The β term is usually an empirical coefficient that can be obtained from statistics analysis of known event cases. Some value of β for EI and WECC can be found in [16]. An empirical way for calculating frequency deviation Δf is described as follows:

- 1) Locate the event time (T_0).
- 2) Calculate the average frequency of 4-second data prior to T_0 of all the FDRs in the same interconnection where event occurs, and treat it as the pre-disturbance frequency (f_{pre}).
- 3) Calculate the average frequency of 4-sec data of all the FDRs in the interconnection between 7 and 11 seconds after T_0 , and treat it as post-disturbance frequency (f_{post}). Seven seconds after T_0 is the empirical value to avert the effect of the transient frequency data.
- 4) After the two frequency averages are obtained, the multiplication of the frequency deviation ($f_{pre} - f_{post}$) and the frequency response characteristic β will yield the estimated trip amount.

2.3. Angle-based Event Location Triangulation with TDOA

The dynamic information in frequency measurements during disturbance has been used for event location estimation and applied on the FNET system with satisfactory accuracy [10]. Considering the mathematical relationship between FNET angle and frequency measurement, it is possible to formulate a practical event location algorithm utilizing phasor angle data instead of frequency measurement. In Section 2.3 ~ Section 2.5, the new event location methods using the FNET angle measurements are proposed, and tested in Section 2.6. We wish to take a fresh step in the direction of developing a reliable and comprehensive method of using real-time wide-area angle measurements to locate the approximate location of power system disturbances.

2.3.1 Features of FNET Angle Data

The FNET phase angle measurement can be represented in the following equation:

$$\theta(t_i) = \int_{t=t_0}^{t_i} 2\pi(f - f_0)tdt + \theta_0 \quad \text{Eq. 2-2}$$

where f_0 stands for the nominal frequency (60Hz in North America). The phasor rotates at angular velocity of $2\pi(f - f_0)$. The phase angle will grow monotonically during steady state when the frequency is not exactly 60Hz, as shown in Fig. 2-4.

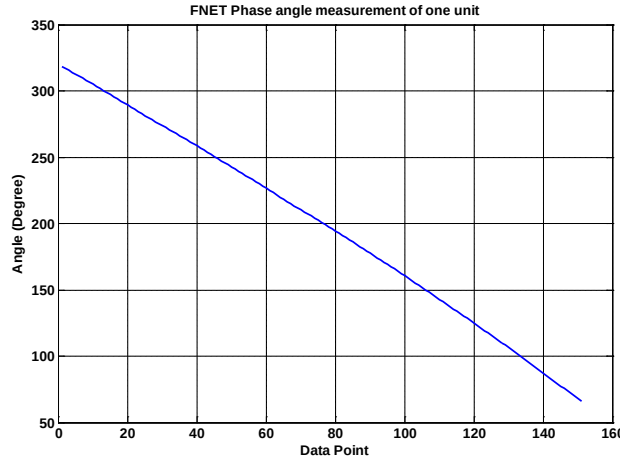
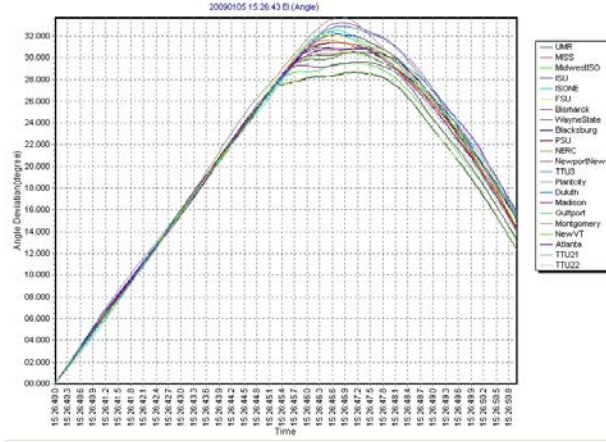


Fig. 2-4. FNET Phase Angle Measurement

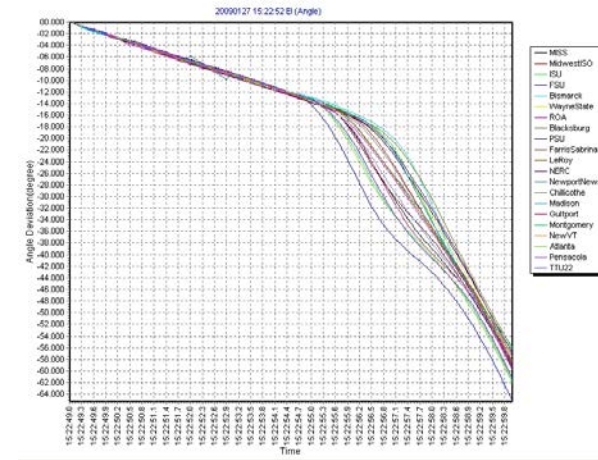
When some disturbance occurs in the power system, the frequency measurements will increase or drop according to event types, since phase angle is the integration of frequency deviation from nominal value (60Hz) over time, the angle data also demonstrate dynamic behaviors before and after disturbance point. Here we only consider two types of disturbances:

generator trip and load shedding. For example, Fig. 2-5 shows the unwrapped FNET angle data during generation trip transient period.

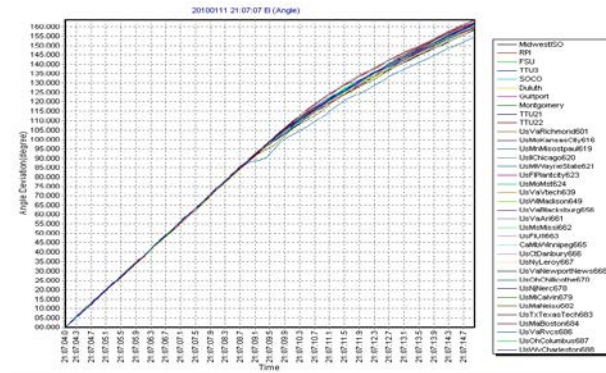
As the integral of frequency deviation over time, a small change in frequency will cause relatively large changes on angle measurement, a better signal-to-noise ratio (SNR) will be obtained on angle measurement. A better performance is expected for angle-based event location method. Such scenario is also observed in the area of power system oscillation detection and oscillation analysis [11].



(a) $F_{\text{beforeevent}} > 60\text{Hz}$; $F_{\text{afterevent}} < 60\text{Hz}$



(b) $F_{\text{beforeevent}} < 60\text{Hz}$; $F_{\text{afterevent}} < 60\text{Hz}$



(c) $F_{\text{beforeevent}} > 60\text{Hz}$; $F_{\text{afterevent}} > 60\text{Hz}$

Fig. 2-5. FNET Angle Data Changes during Generation Trips

It is necessary to note that the angle curves shown in Fig. 2-5 have gone through a set of data processing procedure, including angle unwrapping, angle normalization, median filtering, etc, to be discussed in Section 2.3.2.

2.3.2 Phase Angle Data Processing

Since the absolute FNET phase angle measurement cannot reveal disturbance dynamics as directly as frequency measurement, several data processing steps need to be taken in order to extract dynamic information from wide-area angle measurement. In the section, the detailed processing steps are discussed.

The voltage phase angle after these data processing steps presented in this section is in a different manner from that in conventional power system analysis. Conventionally, voltage angle is used in the way of referencing to some swing or slack bus in the system (e.g. TVA's Brown's Ferry nuclear generating station for EI studies and Palo Verde nuclear generating station in the WECC). However, in this analysis, we process FNET angle measurements in terms of self normalization, and slope de-trending, etc.

2.3.2.1 Angle Unwrapping

The value of FDR angle measurements are constrained between 0 and 2π , which causes sudden angle jumps when the measurement crosses the boundary of the value range, as shown in Fig. 2-6. It is necessary for restore angles back to monotonically growing trend within the time frame for event location estimation, we call the process as angle unwrapping.

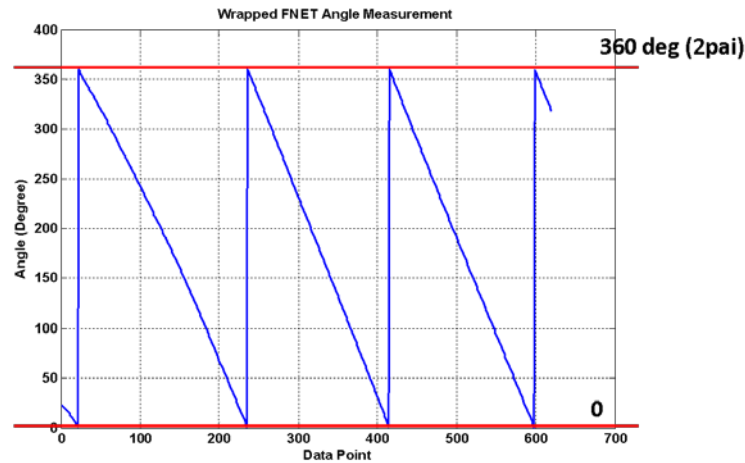


Fig. 2-6. Wrapped FNET phase angle measurement

Fig. 2-7 shows the flowchart of the angle unwrapping routine. The algorithm is to keep track of the angle jumps, and count the jumps into an unwrapping parameter $m_fUnwrap$. If it is a negative jump, which means the angle changes from near 2π to just over 0, one more 2π needs to be added to $m_fUnwrap$ to keep the angle monotonic increasing. If it is a positive jump, which means the angle changes from just over 0 to near 2π , one more 2π needs to be

subtracted from $m_fUnwrap$ to keep the angle monotonic decreasing. The sum of the unwrapping parameter $m_fUnwrap$ and the original angle measurement is the unwrapped angle data.

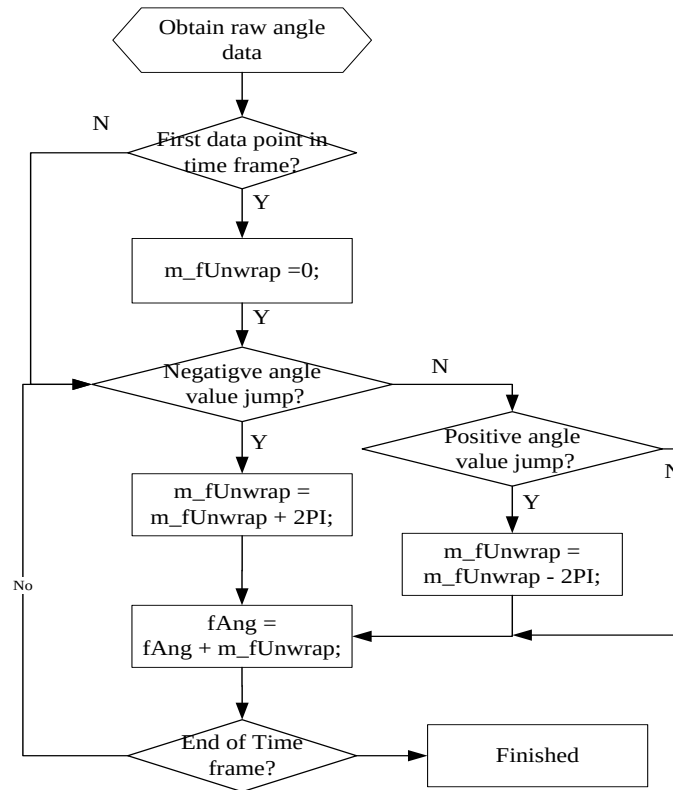


Fig. 2-7. Flow chart of FNET Angle Unwrapping

2.3.2.2 Adaptive Angle Sawtooth Calibration

The data accuracy and integrity is the foundation of the success of any power system applications. Since the 1st generation FDRs use old firmware and there exists problems on the angle measurement, which is referred to as “sawtooth”. The angle plot in Fig. 2-8 shows the signatures of angle data with sawtooth, which display curves cluttered by the sawtooth with abrupt turns. We need to estimate and rectify the sawtooth error before angle data being used for further event location applications.

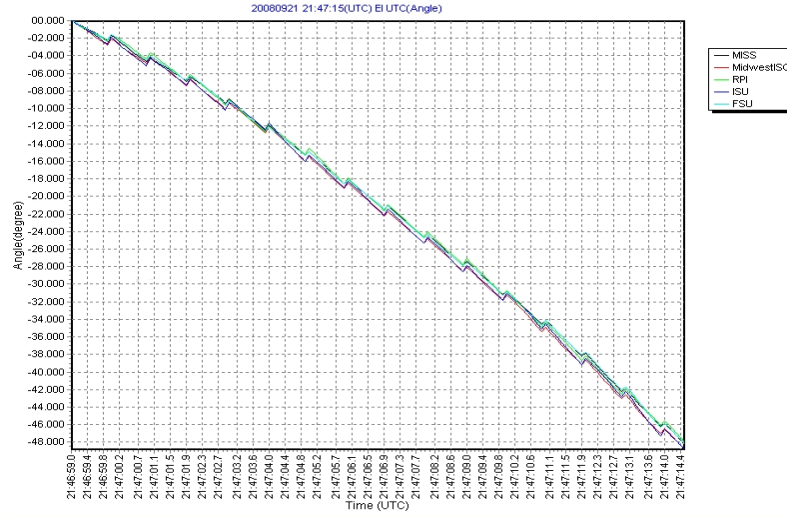


Fig. 2-8. Demonstration of Unwrapped Angle Data with Sawtooth

Because the sawtooth errors are linear with the data point index, we can compensate the errors by subtracting the erroneous amount corresponding to the linearity of the errors. However, the starting point and sawtooth periodic cycle length is floating even when the sawtooth error grows linearly with data point index. In most cases the starting point of one sawtooth period starts at the first or second data point in one second periodic cycle, just as shown in Fig. 2-9.

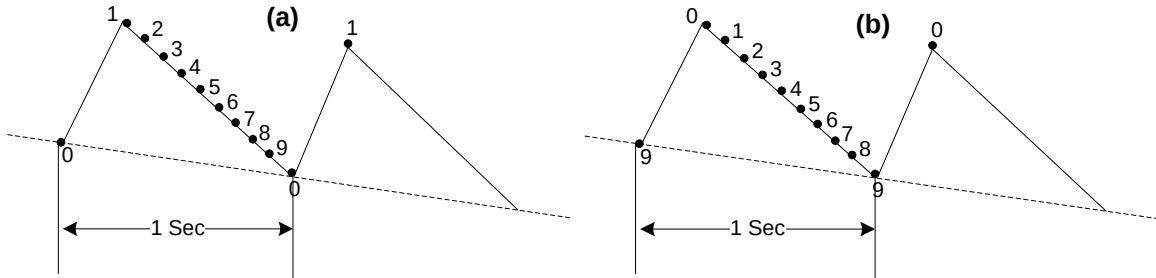


Fig. 2-9. Two Sawtooth Cycle Patterns of FNET Angle Data

Here we use the adaptive sawtooth calibration method to firstly identify the sawtooth periodic cycle length, the cycle starting point, calculate the sawtooth offset, and then calibrate the sawtooth with these offset estimations. Fig. 2-10 shows a general sawtooth error plot. Assume that the sawtooth period cycle is N , starting point is i_0 .

In Fig. 2-10, the solid black curve is the FDR phase angle measurement, and the dash black straight line is the right angle value. The goal is to bring the measurement from solid line to the black dash straight line. More specifically, the slope β between the solid straight line and the dash straight line is the coefficient that the sawtooth calibration procedure needs to amend the measurements with. The coefficient β can be obtained by subtracting α from γ .

Note that the linear slope α is caused by a constant frequency deviation from nominal frequency.

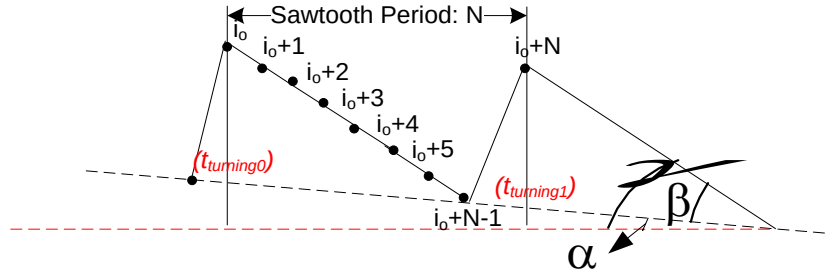


Fig. 2-10. Illustration of Solution of Sawtooth Error

Before calculation of α and γ , the sawtooth cycle N and starting point i_0 need to be indentified at first, which means we need to identify the abrupt turning points and interval between two consecutive abrupt turning points. In order to do so, the value difference between two consecutive angle data will be checked against a pre-defined threshold, if over the threshold, the first abrupt turning point is detected. The saw tooth cycle will be further identified when a second abrupt turning point is detected with the same method.

As a summary, the procedure of rectifying saw tooth error is:

Step 1: Calculate the difference between two time consecutive angle data $d\theta(t) = |\theta(t) - \theta(t-1)|$, when $d\theta(t)$ is larger the some threshold, the first turning point is detected as $t_{turning0}$, as indicated in Fig. 2-10;

Step 2: Keep checking angle difference until a second turning point is detected, named as $t_{turning1}$, as indicated in Fig. 2-10;

Step 3: The saw tooth cycle is calculated as $N = t_{turning1} - t_{turning0}$, and the sawtooth starting point is set as $t_0 = t_{turning0}$;

Step 4: Calculate $\frac{\theta(t_0 + kN) - \theta(t_0 + (k+1)N)}{N}$ and write down the quotient as α .

Step 5: Calculate $\frac{\theta(t_0 + kN) - \theta(t_0 + kN + m)}{m}$ ($0 < m < N$) and count the quotient as γ .

Step 6: Subtract α from γ , count the result as β , which is the compensation coefficient we need for sawtooth calibration.

Step 7: After the coefficient β is obtained, for the k^{th} data point in one sawtooth cycle, the compensated angle is calculated as $\theta_k - (N - k) * \beta$.

Note that in order to suppress the noise effect on the quotient calculation (α, γ) , the quotient can be estimated for multiple cycles (such as 5 cycles), and take the average values as the final calibration parameters.

2.3.2.3 Treatment of missing angle data and noise suppression

The event location estimation requires time-continuous angle data from different FDRs, however, due to all kinds of problems, e.g. loss of GPS signal, random communication problem, FDR firmware issue, etc; it is common to have sub-seconds, seconds, even minutes of missing data. And the FDR measurement is not immune from noise. Therefore, before the angle data is applied for event location estimation, it needs to be processed for missing data reconstruction, noise suppression.

According to Eq. 2-2, the frequency stays stable under steady operation state; the angle measurement grows linearly, so the linear interpolation method is adopted for missing angle data construction. However in order to limit the distortion introduced during reconstruction, we set a tolerance level for the maximum data missing points, such as MAXMISSINGNUM, which means if the number of missing data points is smaller than MAXMISSINGNUM, the linear interpolation procedure will proceed, otherwise just abandon the angle measurement from this very FDR. And a 5-point median filter is used for the noise suppression and outlier filtering.

2.3.2.4 Angle Data Self Normalization

Fig. 2-11 shows the absolute phasor angle from different FDRs of a generation trip event case, with angle unwrapped and sawtooth calibrated. The FNET phase angle is a dynamic parameter that rotates at angular velocity of $2\pi(f - f_0)$, where f_0 stands for the nominal frequency (60Hz). Due to different initial phase angle in different FDR locations, and angle shifts from high-voltage transmission networks to distribution levels, the absolute phase angles lay far apart from each other although they have the similar slope due to the synchronized frequency at different locations as seen from Fig. 2-11. Although we can tell the turning point in reaction to the disturbance from each curve, the quantitative differences of the responding times of FDRs to the system disturbance are inundated by these far-apart initial values. We need to bring them to a same level for comparison.

Here a two-step angle data processing method will be taken to expose the dynamic signatures of angle data during power system disturbances. One is self-normalization; the other is slope de-trending or virtual angle referencing.

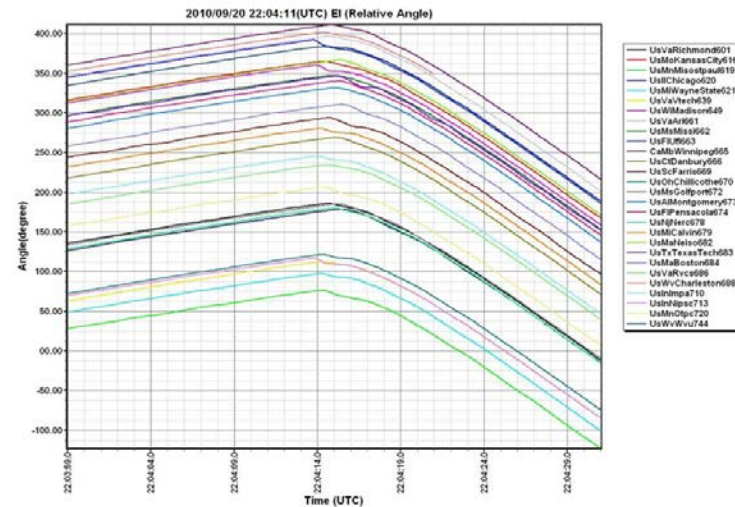


Fig. 2-11. Unwarpped FNET angle measurement for generation trip of 09/20/2010

At first, we intend to eliminate the inconsistent starting angle values among all FDR angle measurements. A simple and straightforward way is to take the first angle measurement of each FDR in the time frame as the reference value of each FDR, and then this reference value will be subtracted from following instantaneous angle value; we call it “self-normalization”. After self-normalization, each FDR’s angle measurement is normalized to start from zero degree, as shown in Fig. 2-12.

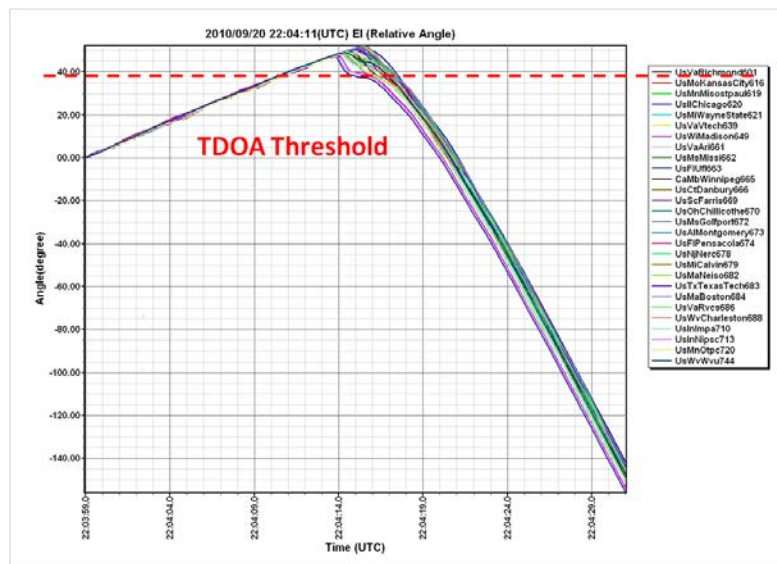


Fig. 2-12. FNET angle measurement after self-normalization for generation trip of 09/20/2010

Now from Fig. 2-12, we can tell the time sequence of FDRs in reaction to the generation trip more easily than Fig. 2-11. Time delays of these sudden angle changes between different locations prove that there also exist the wave propagation signatures in the angle respect.

2.3.2.5 Angle Data De-trending

In order to achieve the estimation of the hypocenter of power system disturbances, we need to get the quantitative wave-front arrival time or Time Delay of Arrival (TDOA)[18][10], which is the time when each FDR detects the disturbance. The accuracy of TDOA determination and the responding sequences of FDRs play a critical role in the TDOA-based event triangulation algorithm which will be discussed in Section 2.3.4.

For the frequency measurement, a pre-defined frequency drop or rise, e.g. 0.014Hz, from previous steady-state frequency value is adopted as the threshold to determine if a frequency wave has arrived at each FDR. However if such method is adopted for angle data, as the red dash line in Fig. 2-12, problems will arise. The angle measurement presents in a quite different way from frequency measurement. The frequency measurement usually stay steady and close to nominal frequency most of time, while the angle data keep monotonically increasing or decreasing (Fig. 2-12), there is no uniform way to set a threshold for angle data.

To ease the difficulty of the threshold setting, we intend to remove the angle monotonic increasing or decreasing trend before disturbance point and still keep the dynamic signatures. A reference angle needs to be set up. Instead of using any single FDR's measurement as reference, a set of virtual referencing angle is calculated. The virtual reference angle is assumed to rotate at angular velocity of $2\pi(f - f_0)$, where f is the frequency before disturbance point. In other words, the virtual reference angle is not affected by the disturbance; it will grow monotonically and keep the pre-disturbance slope. The linear fitting method is applied to identify the slopes and construct the virtual reference angle. As shown in Fig. 2-13, the basic procedure works as follows:

- 1) Set a time frame, say 4 sec before event time;
- 2) Calculate the median angle out of all FDR measurements as the red solid line shown in Fig. 2-13.
- 3) Calculate the slope of the median angle.
- 4) Using the estimated slope to construct the virtual angle reference.

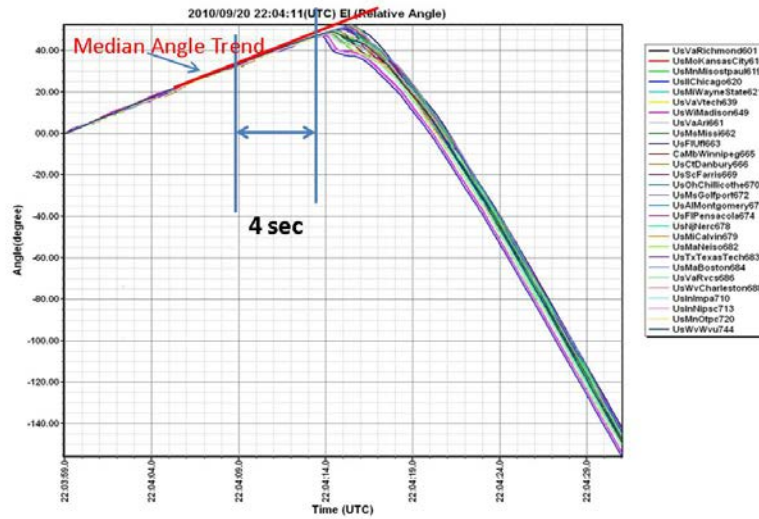


Fig. 2-13. Illustration of virtual reference angle estimation for event location estimation

The FDR phase angle after referencing to the virtual angle is shown in Fig. 2-14. Taking the pre-disturbance angle trending curve as reference, it is able to determine how quickly the FDR angle measurements deviate from pre-disturbance status in reaction to the disturbance. Here we only care about how quickly these measurement deviates from the virtual reference angle, not the deviation direction, so the absolute value of the angle deviation is taken. Fig. 2-15 shows a close-up view of the angle measurement nearing the disturbance time, which clearly shows the angle perturbation propagation.

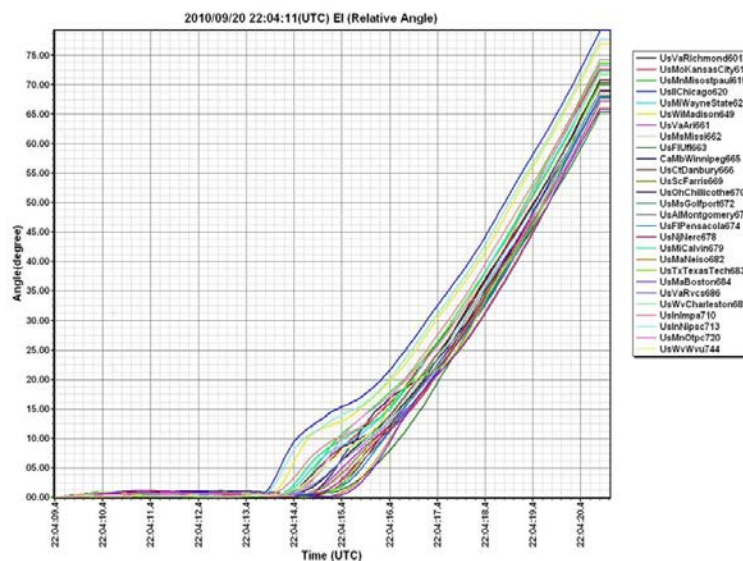


Fig. 2-14. FNET phase angle after referencing to virtual angle (de-trending)

located throughout the grid detect said waves with unique time delays proportional to the physical distance from its location to the disturbance center, which is named as “wave-front arrival times”. The wave propagation phenomenon is also observed in angle data, as shown in Fig. 2-15.

The precisely GPS-synchronized time stamps on each measurement data makes the determination of the so called “wave-front arrival time” possible and accurate. Technically the determination of the “wave-front arrival times” is determined by the time when the angle data surpass certain threshold. Here we set the detection threshold as a confidence threshold ε plus the average value of angle measurement within certain time window before event time.

As a summary, the wave-front arrival time is detected in the following procedure:

Step 1: After the on-line event trigger detects an event, three seconds worth of angle data before event trigger time is used to calculate the pre-disturbance average angle, as shown in the following equation. In most cases, the $\overline{\theta_{pre}}$ stays close to zero.

$$\overline{\theta_{pre}} = \frac{1}{N} \sum_{i=1}^N \left(\frac{1}{k} \sum_{j=1}^k \theta_{i,j} \right) \quad \text{Eq. 2-3}$$

where N is the total number of available FDR units at the very time, k is the number of data points used for averaging, i is the index of FDR units, j is the index of data point, $\theta_{i,j}$ is the corresponding j^{th} angle data of unit i .

Step 2: A confidence threshold ε , has been fixed between 3.2 – 0.8 degree, which is justified empirically by historically archived event cases in FNET system. Then, the wave-front arrival time detection threshold, is calculated with $\overline{\theta_{pre}}$ plus ε . This quantity is defined as:

$$\theta_{wavefront} = \overline{\theta_{pre}} + \varepsilon \quad \text{Eq. 2-4}$$

Step 3: The wave-front arrival times are identified as the time when the angle data crosses the line defined by $\theta_{wavefront}$. The illustration of wave-front arrival time difference is shown in Fig. 2-17. The red dash line indicates average of all units' angle measurements before event; the solid blue line presents the detection threshold for determination of wave front arrival time.

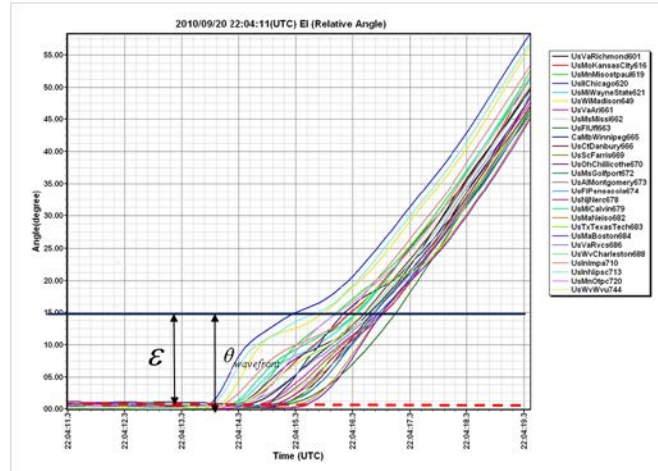


Fig. 2-17. Example of Wave-front Arrival Time Detection Method with Fixed Threshold

The Wave-front Arrival Time is also called Time Delay of Arrival (TDOA) in FNET system. In the following section, these two terms may be used alternately. The chart in Fig. 2-18 illustrates the characteristics of Wave-front Arrival Time for one generation trip event (BRAIDWOOD plant trip of 09/20/2010). The X axis shows the wave-front arrival times of different FDRs, after referring to the first unit. The Y axis is the geographic distance from each unit to the actual tripped generation plant (BRAIDWOOD). It can be seen from this chart that the red solid are approximately linearly distributed, which reflects the proportionality between FDR distance to event location and TDOA.

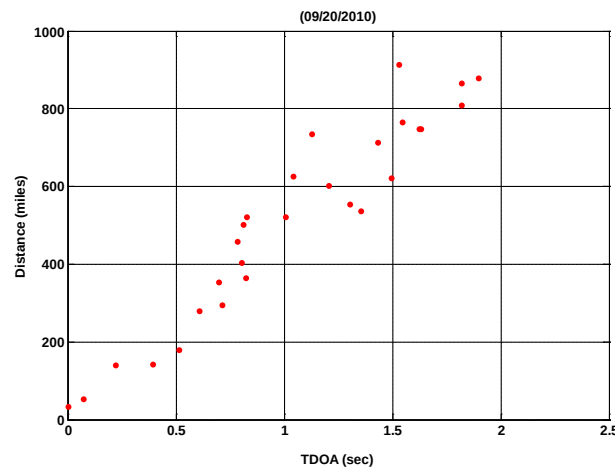


Fig. 2-18. Chart of Distance between FDR and Event Center vs. TDOA for Braidwood trip of 09/20/2010

However, the proportionality will probably be affected by many factors, for example noise, system topology, the disturbance level, the precision of sensors, etc. There is a very common pattern that the closer the units to the event location the more proportional their TDOAs are to their distances to the disturbance location, which is justified empirically by FNET historical event

cases [18]. So in the practical event location algorithm design, only the information of the first several units will be utilized.

2.3.4 Event Location Triangulation with TDOA

The event location triangulation method is based on geometrical triangulation algorithm which utilizes the wave-front arrival times and geographical location information of each FDR and . As shown in Fig. 2-19, the basic equations used in event location triangulation can be drawn as:

$$L_i = V(t_i - t_e) \quad \text{Eq. 2-5}$$

$$L_i^2 = (x_i - x_e)^2 + (y_i - y_e)^2 \quad \text{Eq. 2-6}$$

Where the L_i is the distance between FDR_i and the event hypocenter, and x_i and y_i are the latitude and longitude of FDR_i location respectively, t_i is the wave-front arrival time determined of FDR_i and t_e is assumed as the actual event time. Note that t_i is strictly larger than t_e since the event cannot be detected before it occurs. V is the wave propagation speed. For simplification, we assume the wave propagation speed, V , is unique in the system.

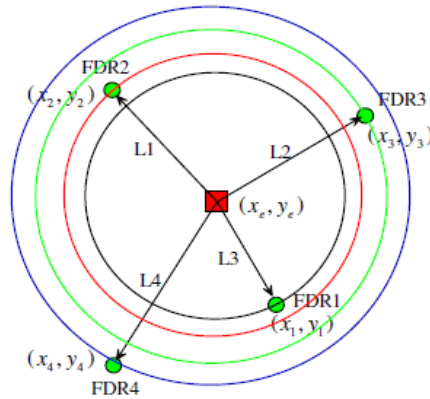


Fig. 2-19. Chart of event location triangulation method

With the wave front arrival time (t_i) and FDR geographical information (x_i, y_i) known, The Least Squares Methods can work as a solution for Eq. 2-5, Eq. 2-6, which will pinpoint the most possible event location.

2.3.4.1 Least Squares Method

From Eq. 2-5, Eq. 2-6, we can draw the following set of equations:

$$\begin{aligned}
(x_1 - x_e)^2 + (y_1 - y_e)^2 &= V^2(t_1 - t_e)^2 \\
(x_2 - x_e)^2 + (y_2 - y_e)^2 &= V^2(t_2 - t_e)^2 \\
&\vdots \\
(x_n - x_e)^2 + (y_n - y_e)^2 &= V^2(t_n - t_e)^2
\end{aligned}
\tag{Eq. 2-7}$$

The unknowns in the above equation set are: the hypocentral coordinates (x_e, y_e) , and the time t_e when the event occurred.

In general, the equation set will be over-constrained since typically many more FDRs respond than there are variables. As the next step, we will try to change the non-linear equations in Eq. 2-7 into linear forms, by subtracting successive pairs of equations; a linear equation in terms of the hypocenter coordinates is produced as:

$$(x_{i+1} - x_i)x_e - (y_{i+1} - y_i)y_e - V^2(t_{i+1} - t_i)t_e = C_i \tag{Eq. 2-8}$$

Where C_i is defined as:

$$C_i = \frac{1}{2} [V^2(t_{i+1} - t_i) + x_{i+1}^2 + y_{i+1}^2 - x_i^2 - y_i^2] \tag{Eq. 2-9}$$

Hence, Eq. 2-9 can be written for every FDR unit that responds, then the set of equations can be organized into Matrix form:

$$\mathbf{C} = \mathbf{H}\mathbf{x} \tag{Eq. 2-10}$$

Where the matrix variables are defined as:

$$\mathbf{C} = \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} x_h \\ y_h \\ t_h \end{bmatrix} \tag{Eq. 2-11}$$

$$\mathbf{H} = \begin{bmatrix} x_2 - x_1 & y_2 - y_1 & V^2(t_2 - t_1) \\ x_3 - x_2 & y_3 - y_2 & V^2(t_3 - t_2) \\ \vdots & \vdots & \vdots \\ x_n - x_{n-1} & y_n - y_{n-1} & V^2(t_n - t_{n-1}) \\ x_1 - x_n & y_1 - y_n & V^2(t_1 - t_n) \end{bmatrix} \tag{Eq. 2-12}$$

To solve $\mathbf{x}$ in Eq. 2-10 which contains the hypocentral coordinates, we use the pseudo-inverse matrix defined as:

$$\mathbf{H}^{\dagger} = (\mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \quad \text{Eq. 2-13}$$

The final least squares solution is:

$$\mathbf{x} = \mathbf{H}^{\dagger} \mathbf{C} \quad \text{Eq. 2-14}$$

Although it is possible to use as much as possible units for the least square methods, the proportionality between wave arrival time ($t_i - t_e$) and distance (L_i) is deteriorating as the units locate far from the hypocenter of disturbance[18]. In light of that phenomenon, only the first several units are used for location triangulation. Practically, the first 6 has been proven to be an empirical number to ensure proportionality based on historical event cases in FNET system [18].

One more step needs to be taken to verify that the solution is practically reasonable in power system area. The criterion used for validation is: 1) the event time (t_h) should be smaller than t_1 . 2) The distance between the estimated event location (x_h, y_h) and the first FDR unit should be within certain range (e.g. 200miles); 3) the propagation speed (V) should be within certain range (e.g. 200-1000).

The least squares method is treated as a general solution for event location triangulation, which will give out most possible event location in the form of latitude and longitude. In the next section (Section 2.3.4.2), a more specific method is introduced for identifying the tripped generation plant or pumped hydroelectric storage unit.

2.3.4.2 Plant-aided method

With respect to the disturbances triggered by generation plant trip or pumped hydroelectric storage units, it is expected to pinpoint the specific tripped plant or hydroelectric storage unit name and its geographical location, instead of reporting a general location (e.g. latitude, longitude).

According to previous observations, the first FDR unit that detects the disturbance is usually the closest one to the actual event location. Therefore we can have the assumption that the possible event location would be within such area that any spot in it be sufficiently close to the first FDR unit. We can approximately get such area by drawing a suitable circle (with radius r) centering the first responding FDR unit. An empirical value of 200 miles is set as the radius r . With more FDRs being distributed, the radius r can be narrowed down.

Take the generation trip disturbance as example, at the first step, a database containing the generation plant information is created, which includes plant capacity, plant name, plant location, etc. Then this plant-aided approach works in the following steps.

1. Plant Pre-selection

When the disturbance is determined as a generator trip and the generation drop amount is estimated, the possible tripped generation plants can only be located within the circular area centering the first responding FDR, with its capacity larger than or close to the estimated trip amount. By filtering out power plants with capacity under trip amount and those out of geographical range, the candidate pool will be narrowed down to only a few power plants and therefore make the next validation step more efficient.

2. Proportionality Validation

After the candidate pool is chosen, the proportionality of TDOAs of FDRs and their physical distances to the disturbance location, namely these generation plants, are checked to further select the most possible tripped plant. Linear regression is a popular approach for linearity validation, and the residues for linear fitting can be used as the indicator of the proportionality of the points concerned.

In this approach, each possible power plant is assumed to be the hypothesized event location, and the linear regression is performed, residues are obtained. The event location can then be finalized by choosing the power plant that has the minimum residue.

In summary, the plant-aided approach can be described as follows:

- 1) Assume a generation trip occurs at the red star and the six FDRs in Eastern Interconnection with earliest TDOAs are indicated with green cross.



Fig. 2-20. Illustration of plant-aided approach - 1

2) Determine the TDOA of each FDR from angle measurements, and pick up the first unit that detects the event, and then draw a circle with a pre-defined radius centering this unit.



Fig. 2-21. Illustration of plant-aided approach - 2

3) From the generation plant database, select the power plants that have generators whose capacity are over the trip amount, and locate within the circular area, for example the red dots P1, P2, and P3.



Fig. 2-22. Illustration of plant-aided approach - 3

4) Assume the event occurs at plant P1, and calculate the geographic distances from each FDR to the hypothesized tripped plant (P1). Only the first 6 units are considered.



Fig. 2-23. Illustration of plant-aided approach - 4

5) Do linear fitting based on physical Distance/TDOA of the first 6 units, filter out the one that is furthest from the linear-fitting line.

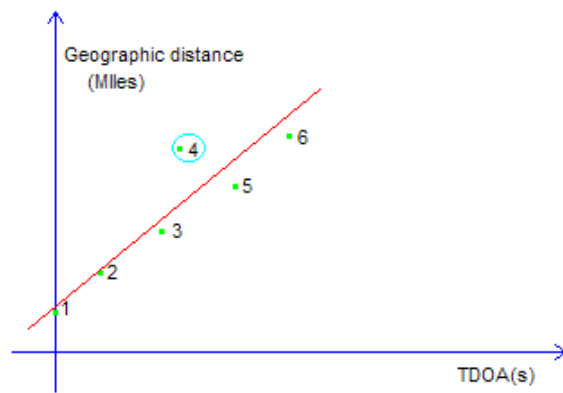


Fig. 2-24. Illustration of first linear fitting between distance and detection time

6) Redo linear fitting based on the Distances/TDOAs of the remaining 5 units. Calculate the residues of linear fitting result.

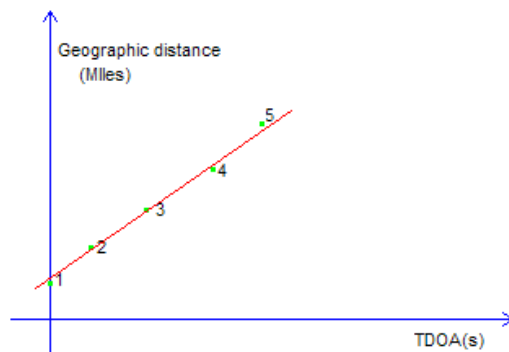


Fig. 2-25. Illustration of second linear fitting between distance and detection time

7) Assume P2, P3 to be the event location respectively, do the same procedure from step 5 to step 6 and obtain the residues for each case.

9) Find the least residues, and the corresponding plant is estimated as tripped generation plant. For example, if P2 has the least residues, we assume it was the event location.

The same procedure works for pumped hydroelectric storage units. To be different from generation trips, there are only a limited number of hydroelectric storage plants with single unit capacity larger than 200MW. Fig. 2-26 shows the geographical distribution of these pumped storage units (blue dots) and the nearby FDRs (red dots). With FDRs located in close proximity to these hydro-electric pumped storage units, the plant-aided method works for identifying the possible pumped storage unit location.



Fig. 2-26. Distribution of Hydroelectric Storage Units and Nearby FDR units

2.3.4.3 Summary

For the event location triangulation using the wave propagation time information, the least-square method and plant-aided method complement with each other. The plant-aided method works as the first step, once it fails, the general event location method, namely the least-square method, will work as the second step to obtain a general event location (latitude, longitude).

2.4. Angle-based Event Location Triangulation Enhancements

As discussed in Section 2.3.4, the successful event location triangulation is greatly determined by the accurate determination of the wave front arrival times of each FDR, especially the FDR unit with earliest wave-front arrival time greatly determines the search area

for event hypocenter. The incorrect wave-front arrival times may introduce a wrong event location estimation result; even fail to reach a valid location. In this section, some approaches are introduced for the triangulation enhancement.

2.4.1 Sequential TDOA detection threshold

The wave-front arrival time determination is of pivotal importance for the estimation of disturbance location. Assume that the electromechanical wave travels approximately at 400 miles per second, it means one second error in deciding the wave-front arrival time can possibly lead to 400 miles error in the event location estimation.

The wave-front arrival time is mainly determined by the threshold setting. However, the power systems are not an ideal system without any oscillatory fluctuation and noise, the magnitude of angle variation differs in scenarios, and the FNET system is not a perfect system immune from noise, errors and misrepresentations. Due to these practical problems, the triangulation algorithm will not always work successfully for one single fixed threshold, or different threshold setting may obtain different event location results.

Take one generator trip event as example, the angle curve during the event transient period is indicated in Fig. 2-27, different detection thresholds are applied. The red dash line indicates the average angle value before event. Two threshold lines are drawn in blue and yellow solid line. It is apparent that the two thresholds cut across two distinct set of FDR units, especially the first wave front arrival unit differs. For the 3.2 degree confidence threshold the unit in Charleston, WV is detected as the first one, while the unit in Blacksburg, VA for 1.2 degree confidence threshold.

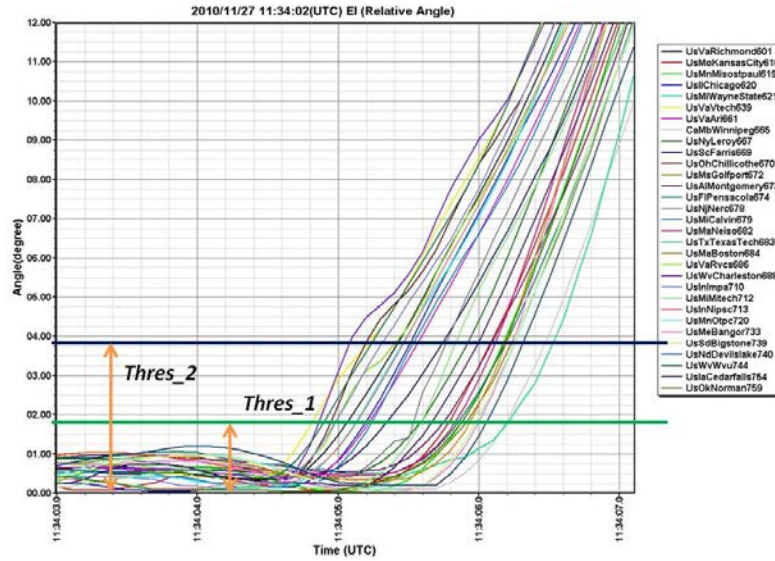


Fig. 2-27. Angle plot the generation trip of 11/27/2010 with different thresholds indicated

One solution of this issue is to use the sequential threshold for wave front arrival time determination, which means that a set of threshold will be attempted sequentially. The algorithm would try the 3.2 degree as confidence threshold first, if it works, the estimated event location will be reported, otherwise attempt the next threshold until one threshold works. If none of the set of thresholds works, the event location triangulation claims failure for this case or resort to other methods. The sequential threshold setting is determined empirically. The threshold sequence is set as: **3.2, 1.2, 3, 2.5, 2, 1.5, 1**. The effectiveness of using sequential threshold has been substantiated by many successful FNET offline or online event cases.

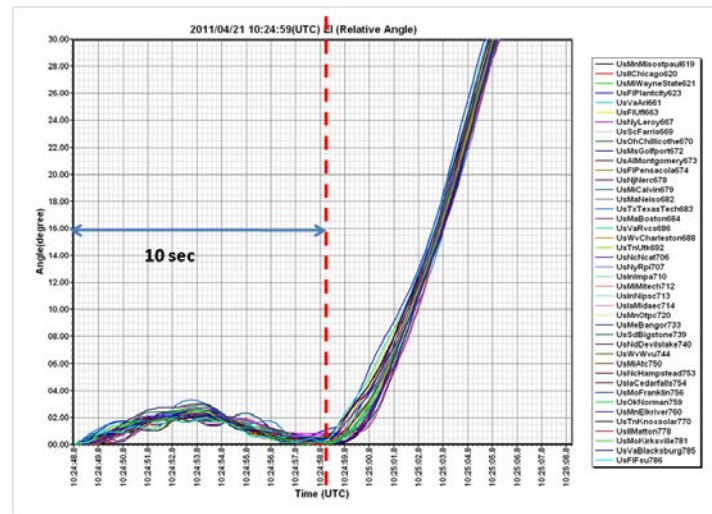
2.4.2 Angle data selection

Although the data processing methods discussed in Section 2.3.2 has prevented certain level of misrepresentation of FNET angle data, and suppressed noise level, the angle data is still not immune from error and noise. During the online or offline experiments, it has been noticed that the phase angle data used for triangulation is sensitive to the choice of angle referencing, especially the choice of starting time frame.

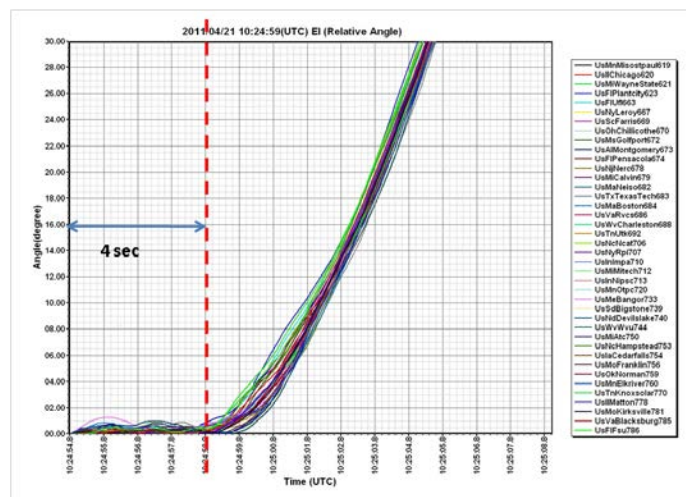
Usually at first we would need a relatively large chunk of data covering the complete transient period for multiple purposes, e.g. event type classification, trip amount estimation, sawtooth calibration, slope fitting, etc, the time frame we take starts from 10 sec before event time to 30 sec after event time. However, considering the data conditioning steps discussed in Section 2.3.2, the more accurate the pre-disturbance angle trend or slope we can obtain

through linear fitting, the more accurate the wave-front arrival time of each FDR will be. The system frequency consistently keep fluctuating even during steady-state, so do the angle data, to avoid introducing extra noise long before the event time to the signal processing procedure, the very time right before the event time is of most critical for trend estimation. In fact, a short time period ahead of event time is sufficient. We take 4 sec before event time as the starting time frame for angle data linear fitting.

Fig. 2-28 demonstrates the effect of different starting time frame. In Fig. 2-28 (a), the time frame starts at 10 sec before event time, and in Fig. 2-28(b) it is 4 sec before event time. It turns out that the angle has larger fluctuation for the time frame starting 10 second ahead than 4 second.



(a) Time frame Starting 10 sec ahead



(b) Time frame starting from 4 sec ahead

Fig. 2-28. Effect of starting reference angle data on relative angle curves

According to the online/offline experiments, the data selection strategy works well, which increase the estimation accuracy and reduce the triangulation failure rate.

2.4.3 Event Time refinement

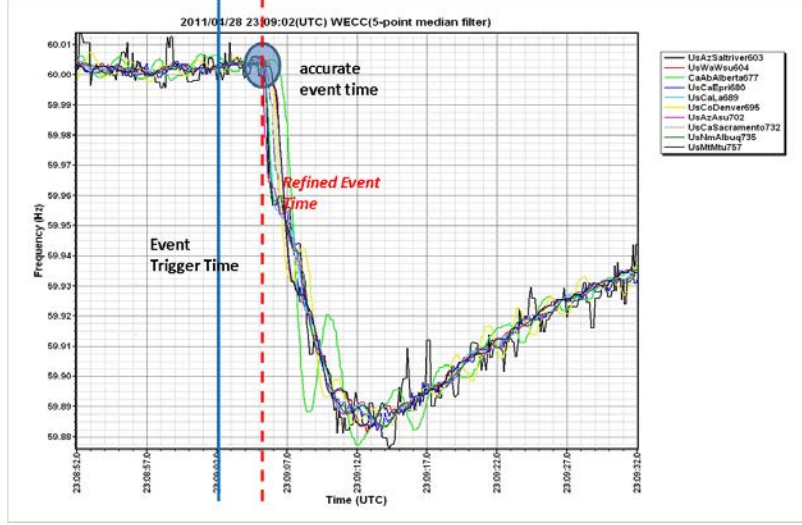
The effectiveness of the data re-selection process (in Section 2.4.2) greatly depends on the accuracy of event time. However during the FNET event trigger process, only a coarse event time is given out, which can be treated as event triggering time. In most cases, this event triggering time is 2~4 sec ahead of accurate event time, as shown in Fig. 2-29.

The refinement of event time can help improve the effectiveness of data selection, eventually the event location triangulation. The accurate event time is defined as the first turning point on frequency or angle curve. Both the frequency and angle data can be used for event time refinement. Here the angle data is utilized for event time refinement.

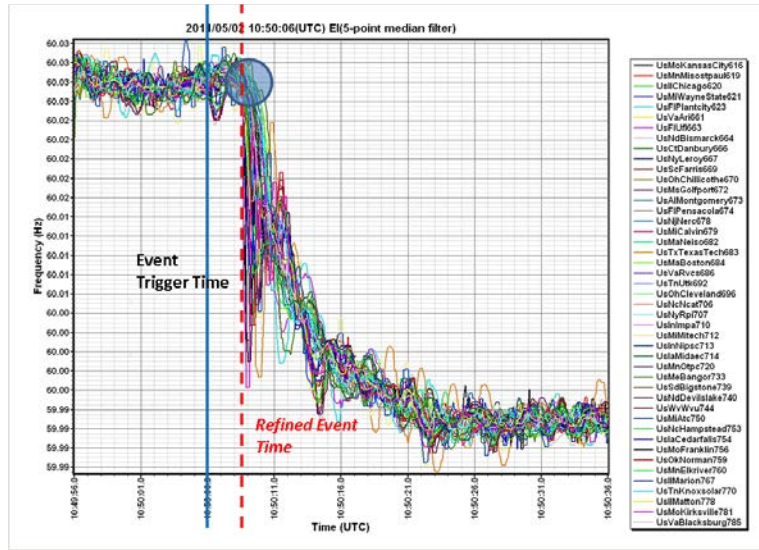
As a summary, the procedures of event time refinement are:

- 1 At the first step, a chunk of data would be selected for refinement, the selected time frame cover from 4 sec before to 4 sec after event triggering time.
- 2 For each FDR unit i , calculate the differential value of the instantaneous angle and five point ahead (0.5 sec interval), which is $d\theta_i(t) = |\theta_i(t) - \theta_i(t - 0.5)|$, when the $d\theta_i(t)$ overpass a pre-defined threshold, the time instant (t) is treated as the turning point for unit i ;
- 3 Check out turning point for each FDR unit, take the earliest turning point as the refined event time;
- 4 If the above steps fail, the event triggering time will be taken as event time to be used in data conditioning procedures.

Fig. 2-29 shows two FNET captured event cases, for which the event triggering time and refined event time are indicated respectively. With the online and offline experiments in FNET system, the event time refinement process does increase the accuracy of event time, and help enhance the performance of angle-based location triangulation.



(a) WECC Generation Trip



(b) EI Generation Trip

Fig. 2-29. Event time refinement for generation trips

One more benefit of the event time refinement is to help improve the accuracy of the trip amount estimation. The trip amount is estimated based on the following equation:

$$P_{Trip} = \beta \times \left| \bar{f}_{beforeevent} - \bar{f}_{afterevent} \right| \quad \text{Eq. 2-15}$$

where $\bar{f}_{beforeevent}$ presents the average frequency before event, $\bar{f}_{afterevent}$ for the average frequency after event. And the time frame for calculation of $\bar{f}_{beforeevent}$ and $\bar{f}_{afterevent}$ greatly depends on the event time.

2.4.4 Summary & Example

All the methods described above collectively serves the angle-based event location triangulation. Fig. 2-30. shows the complete flow chart which coordinates all those methods for event location triangulation.

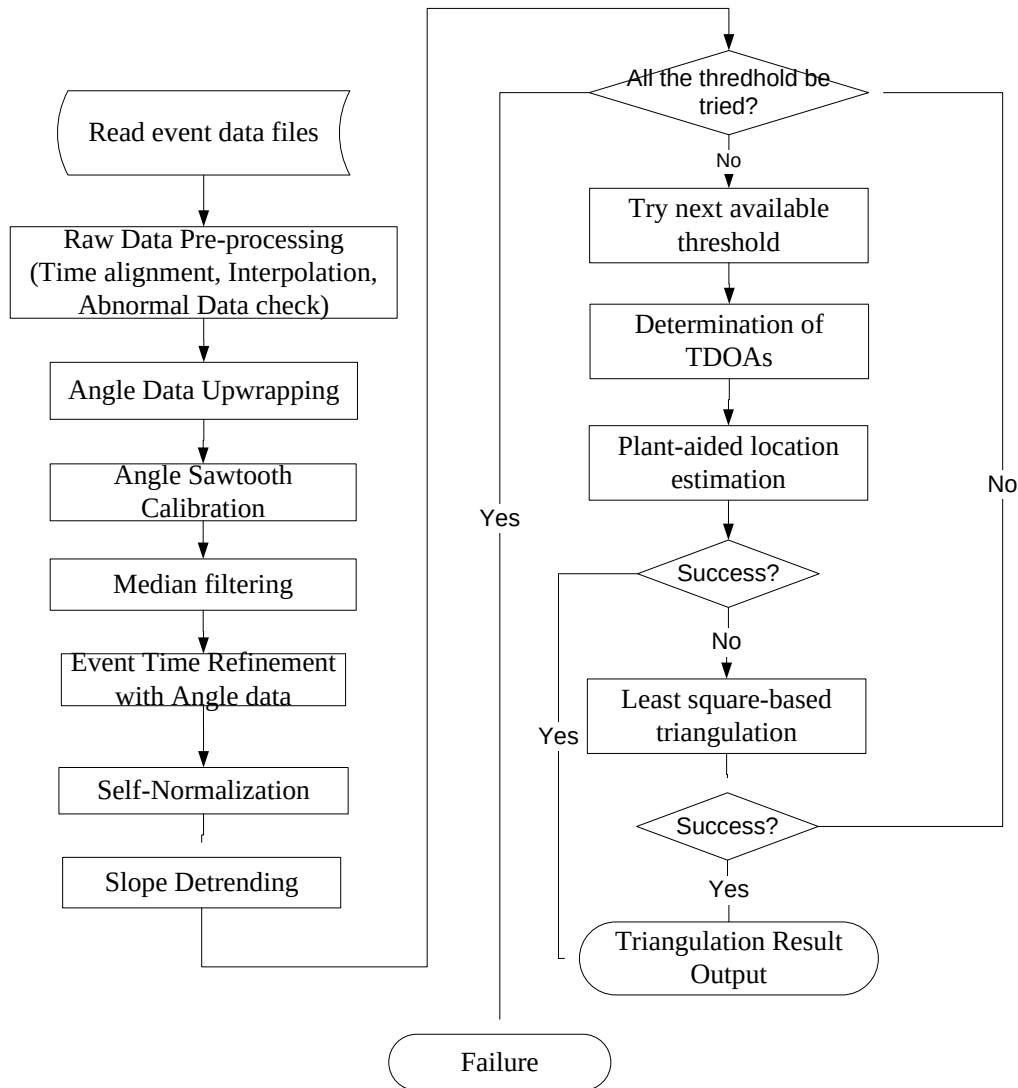


Fig. 2-30. Flow chart of angle-based event location triangulation

Take the generator trip event on 09/20/2010 as example, the corresponding triangulation result from angle-based event location triangulation is shown in Fig. 2-31. The red circle is the possible area in which the disturbance was estimated to occur. The blue dot is the accurate event location confirmed by utilities.

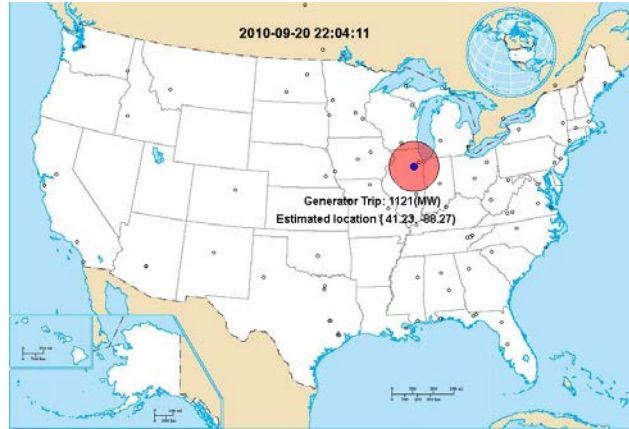


Fig. 2-31. Event Location of the generation trip of 09/20/2010

2.5. Angle-based Event Location Estimation with Oscillation

All the approaches proposed in Section 2.3 and Section 2.4 is based on the relation between the distance and perturbation propagation wave arrival time. The approach proposed in this section will try to obtain the location through exploring another dynamic signature during the disturbance transient period: oscillations.

2.5.1 Basic Principle

It has been known that the accuracy of the identification of the closest FDR to disturbance center plays a critical role for the determination of event hypocenter. The event location triangulation approach in Section 2.3 uses the threshold-based strategy to determine the closest FDR unit based on the wave propagation phenomena. In the section, the closest FDR can be interpreted from another aspect: dynamic oscillatory behaviors during transient period.

A great portion of the power system disturbances, especially the generation loss events, contains obvious oscillations associated with frequency excursions. According to the statistical analysis in [20], the oscillation can be incited by different types of disturbances, e.g. generation trip, load shedding, or line tripping, etc. Fig. 2-32 shows the distribution of the maximum peak angle oscillation magnitude for generation trips in EI from 01/2011 to 09/2011. More than nearly 85% of generation trips have the peak angle oscillation magnitude over 2.5 degree or peak frequency oscillation magnitude over 10 mHz.

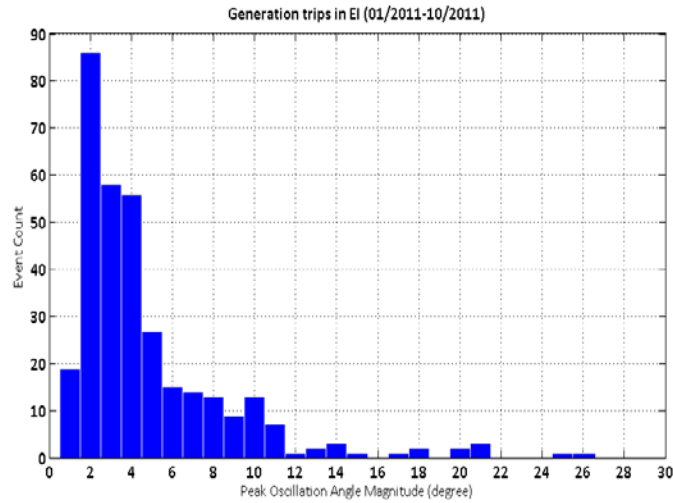


Fig. 2-32. Distribution of maximum peak angle oscillation magnitude for generation trips in EI (01/2011-10/2011)

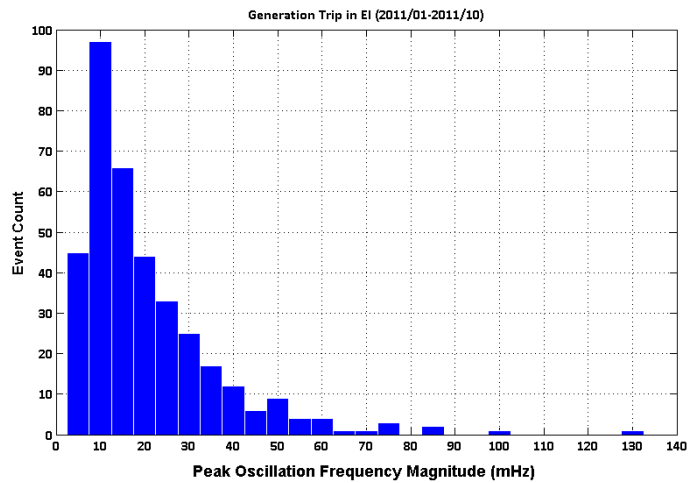
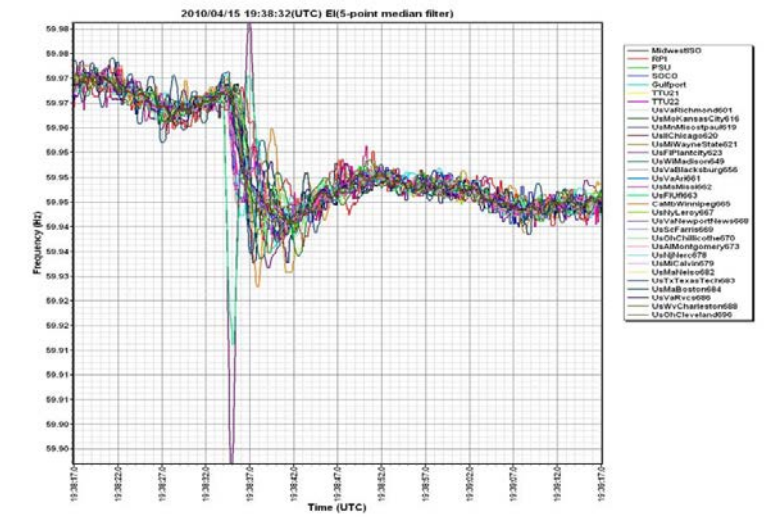
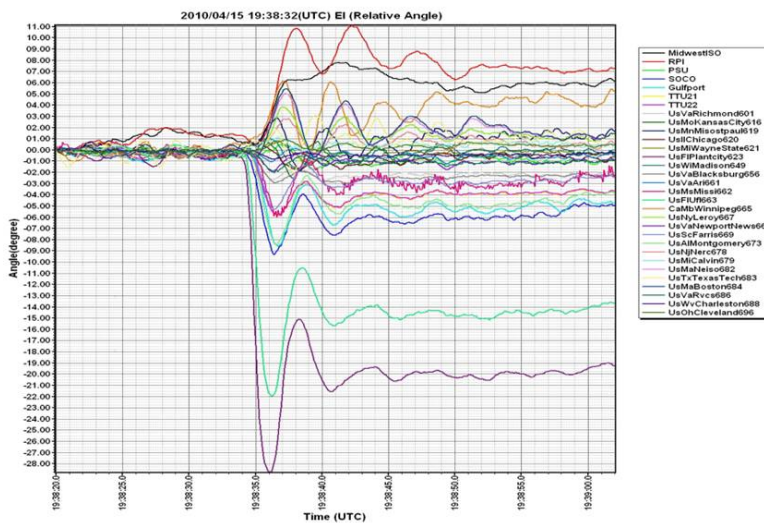


Fig. 2-33. Distribution of maximum peak frequency oscillation magnitude for generation trips in EI (01/2011-10/2011)

Generally, the frequency or angle measurements taken in close proximity to the disturbance center will present a more severe swing than those more distant from the disturbance center. Fig. 2-34 shows the frequency and relative angle curves for the Saint Lucie plant trip on 04/15/2010. The unit located in Plant City, FL (closest to the tripped plant), presented the maximum oscillation magnitude in both angle and frequency measurement, as shown in Fig. 2-35.



(b)Frequency Plot



(b)Relative Angle Plot

Fig. 2-34. Frequency/Angle Plot for Saint Lucie plant trip on 04/15/2010.

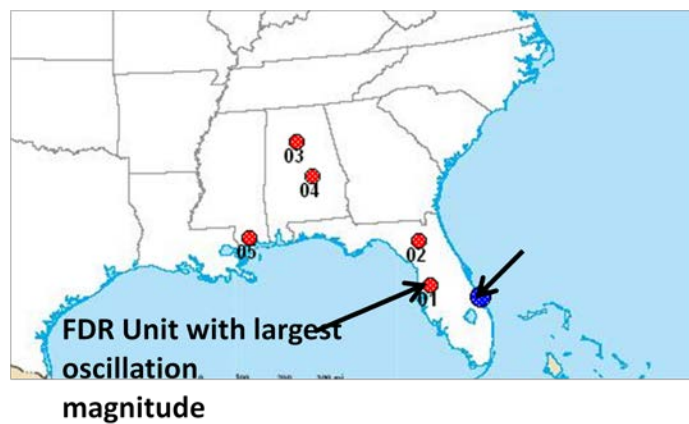


Fig. 2-35. Locations of tripped plant and FDRs with maximum oscillations for Saint Lucie trip on 04/15/2010

This section will address the event location problem from another aspect, which utilize the oscillations associated with frequency excursion to determine the closest FDR unit to event hypocenter, eventually obtain the event locations. Here are several clarifications of the oscillation-based location method:

1) Disturbance Type

Compared with generation trip disturbances, very few load shedding disturbances has obvious oscillation associated [20], so the oscillation-aided event location method only targets at generation trip disturbances with obvious oscillations.

2) Data Source

As shown in Fig. 2-34, both the angle and frequency measurement show oscillations associated with the generation trip disturbance. Considering the better performance on SNR for angle measurement, we use the angle measurement to illustrate the oscillation-based event location method. However, a similar procedure can be also applied on frequency measurement.

2.5.2 Event location estimation based on oscillation information

Both for the frequency and angle measurement, the oscillation and deviation coexist and these two components superimpose up each other during the transient period, our target is to extract, analyze and utilize the dynamic information embedded in the oscillatory component. The basic procedures are discussed as follows:

2.5.2.1 Angle Data Processing

As discussed in Section 2.3.2, the raw FNET angle measurement can not reveal system dynamic information as directly as frequency measurement. A set of data conditioning procedure needs to be performed first. The step 1-3 has been well explained Section 2.5.2

Step 1: Angle Unwrapping

Step 3: Angle Sawtooth Calibration

Step 4: Self normalization

Step 5: Angle data referencing

The median value of all FDR angle measurement at the same time point is selected as the reference angle. For the angle measurement, the referencing can be treated as the de-trending process to extract the oscillatory signature out. Fig. 2-36 shows the relative angle plot

(referencing to the median angle value) for the Saint Lucie plant trip on 04/15/2010. The oscillatory component of each FDR can be clearly observed

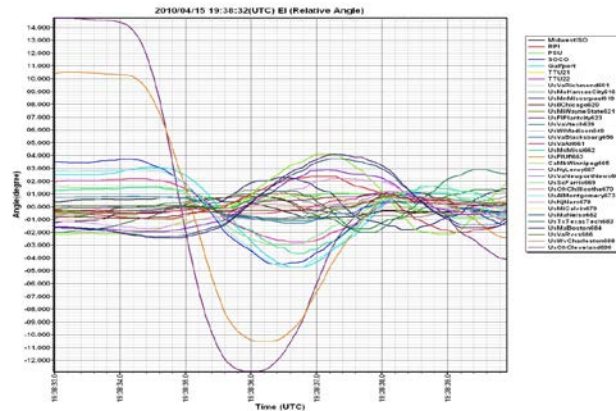


Fig. 2-36. Relative angle plot for Saint Lucie plant trip of 04/15/2010.

2.5.2.2 Oscillation information extraction

In order to use the oscillatory information embedded in relative angle measurement, the quantitative values needs to be extracted from measurement to represent oscillation levels of each FDR, e.g. peak/RMS oscillation magnitude, oscillation modal shapes. Here we will investigate three types of indicator to present the oscillation level of each FDR. These indicators should be effective in helping identify the closest FDR to the disturbance center.

(1) Oscillation Magnitude

The oscillation magnitude is simply treated as the peak value of the oscillation swing each FDR shows, as shown in Fig. 2-37.

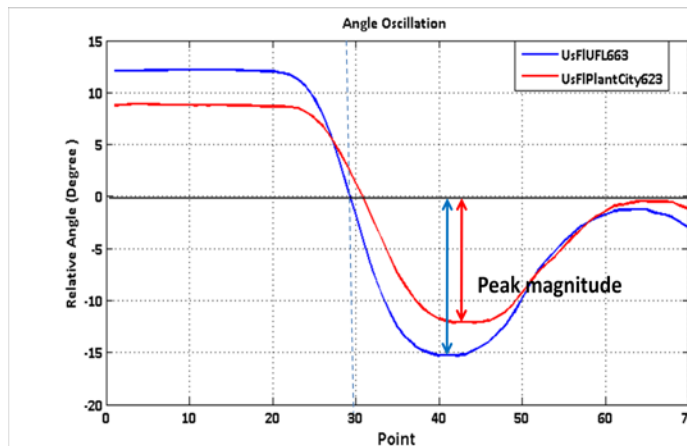


Fig. 2-37. Illustration of Oscillation magnitude for relative angle plot

(2) Average Oscillation Magnitude

Instead of using peak magnitude, the RMS (root mean square) of the varying relative angle over a predefined time frame is calculated to represent the oscillation levels, as shown in Fig. 2-38 and Eq. 2-16.

$$X_{RMS} = \sqrt{\sum_{i=0}^{N-1} x_i^2 / N} \quad \text{Eq. 2-16}$$

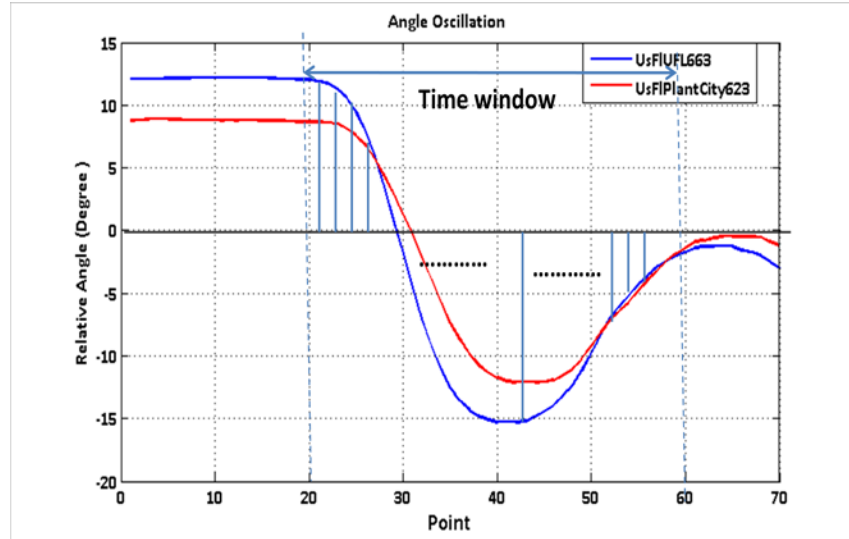


Fig. 2-38. Illustration of calculation of RMS oscillation magnitude

(3) Oscillation Mode frequency/Magnitude

For those FDR units with obvious oscillations, oscillation mode analysis can be performed using various signal processing algorithms, e.g. Matrix Pencil, Prony. In fact only the dominant mode shape is considered here.

Considering all the three above indicators of oscillation levels, some comparison is performed using some historical generation trip events with actual event location known. The comparison is shown in Table 2-1. It only lists the magnitude value, mode analysis result of the FDR unit with maximum value, and its distance to actual event location. The unit is assumed as the closet unit to event location.

Table 2-1 Dominate Mode Freq/RMS magnitude/Peak magnitude/Distances of FDRs of selected generation trips

Event Date	2010/09/02	2010/09/10	2010/10/16	2010/11/28	2010/08/16	2010/07/07
1 st RMS/Dist (degree/miles)	10.75/8.46	4.98/26.58	5.13/73.27	8.41/ 92.60	4.49/34.06	5.02/73.27
1 st Mag/Dist (degree/miles)	15.24/8.46	6.11/26.58	8.24/ 297.33	11.85/292.60	5.94/34.06	6.66/297.33
Domi Freq (Hz)	0.18	0.21	0.22	0.19	0.39	0.36
Event Date	2011/06/06	2011/08/19	2010/11/07	2010/06/18	2011/04/21	2010/10/17
1 st RMS/Dist (degree/miles)	12.97/38.38	6.13/149.98	5.05/159.31	9.08/ 8.46	4.71/73.27	4.78/73.27
1 st Mag/Dist (degree/miles)	21.59/38.38	9.75/456.62	7.12/159.31	11.95/8.46	7.02/499.55	8.02/ 297.33
Domi Freq (Hz)	0.24	0.17	0.19	0.18	0.19	0.22

From Table 2-1, it can be observed that in most cases, the units with maximum peak magnitude and RMS magnitude coincide with each other. The red ones indicate those different ones, from which the RMS magnitude turns out to be more effective in identifying the closest FDR. And in most of cases, the closest FDR determined by RMS magnitude is located within close proximity to the event locations (e.g. within 100 miles). The dominate mode frequency for the unit with maximum RMS magnitude is usually between 0.18-0.4Hz, which belongs to the inter-area oscillation mode.

2.5.2.3 Oscillation filtering

Not all generation trip events have obvious oscillations associated with frequency excursion during the transient period. For these events with trivial oscillation magnitude, the oscillation-based event location method may lead to some results far from the actual event location. In order to avoid these inappropriate applications of the oscillation-based method, a threshold is necessary for filtering out those events with trivial oscillatory behaviors. For example, a threshold of 3 degree can be set for the RMS magnitude, if the maximum RMS magnitude out of all FDRs measurements is smaller than the threshold, the TDOA-based event location triangulation will be applied.

2.5.2.4 Plant-aided location estimation

After the closest FDR being selected as the one with largest oscillatory behavior, a procedure similar to plant-aided approach in Section 2.3.4.2 is applied to determine the tripped plant. Since no TDOA information is obtained here, the power plant with closest proximity to this

FDR and with close capacity to the estimated trip amount is determined as the possible tripped plant.

After considering all the steps in Section 2.5.2, the flowchart of the oscillation-based event location method is described in Fig. 2-39.

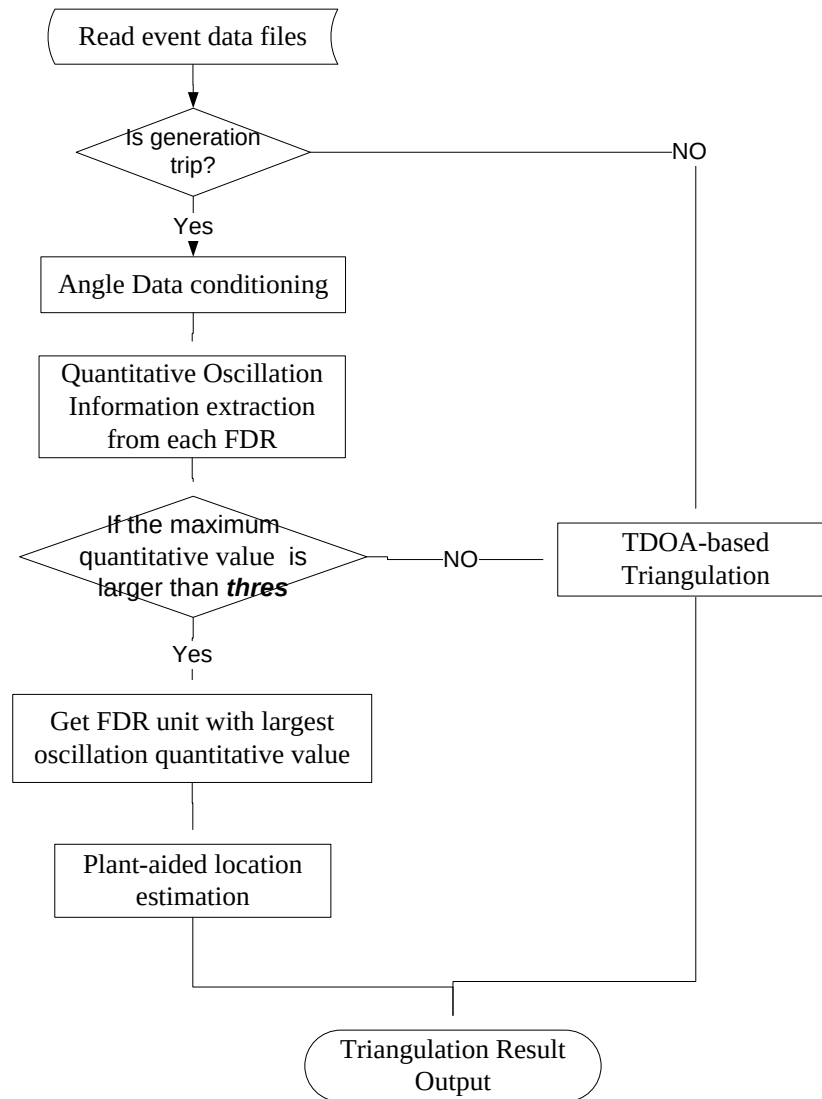


Fig. 2-39. Flow chart of oscillation-based event location estimation

2.5.3 Summary

The oscillation-based event location estimation works well for the generation trips with oscillations associated. It can also be designed as a complementary approach to TDOA-based event location triangulation method. A simply way is to use the oscillation-based event location method as a back-up solution once the TDOA-based method fails on some generation trip

events. The combination of these methods can be referred to as “Oscillation-aided TDOA event location triangulation method”.

All of these approaches (TDOA-based event location triangulation, Oscillation-based event location estimation, Oscillation-aided TDOA-based event location triangulation) use the FNET phase angle measurement to serve the location estimation. The effectiveness will be evaluated with historical FNET events in Section 2.6.

2.6. Performance Evaluation

The effectiveness of the angle-based event location estimation algorithm will be evaluated with historical FNET events. These events have been confirmed by utilities with actual event locations known. The algorithm performance will be compared with frequency-based location method [11][18].

2.6.1 Generation Trip disturbance

There are 94 confirmed generation trip disturbances from 01/2010 to 10/2011 in Eastern Interconnection. The performance evaluation results are listed in Table 2-2. The distance error indicates the geographical distance between the estimated event location and accurate event location. For simplifying comparison, we category the “distance error” into five level, “correct”, “satisfactory”, “acceptable”, “unaccpeactle”, “non-convergent”, which represents distance errors within different ranges.

Table 2-2 Comparation of location estimation results with different methods for generation trips
(2010-2011)

Distance Error (miles)	Correct	Satisfactory	Acceptable	Unacceptable	Non- convergent	Average (miles)
	0	0~100	100~200	>200	--	
Angle-based TDOA Triangulation	15	38	31	9	1	107.78
Oscillation-based location method	17	34	27	15	1	108.27
Freq-based TDOA Triangulation	11	35	25	22	1	184.77

As shown in Table 2-2, the angle-based event location method (Method 1 and Method 2) performs much better than the frequency-based TDOA triangulation method. Nearly 51% of the estimation results are within 100 miles radius from the actual location. Only one generation trip disturbance fails to obtain its location. For this specific event, the failure is caused by the insufficient deployment of FDR around the tripped generation plant. For the oscillation-based location method, the estimation is slightly worse than the pure TDOA location triangulation method. Fig. 2-40 shows the distribution of maximum oscillation magnitudes of the FNET historical events from 2010 to Oct, 2011.

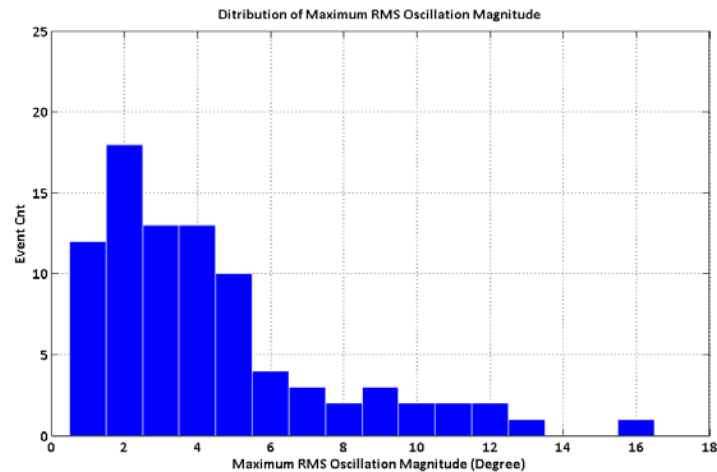


Fig. 2-40. Histogram of RMS Oscillation magnitudes of FNET events (2010-2011)

The histogram plots from Fig. 2-41 to Fig. 2-43 show the distribution of distance errors of the estimation results of these different methods.

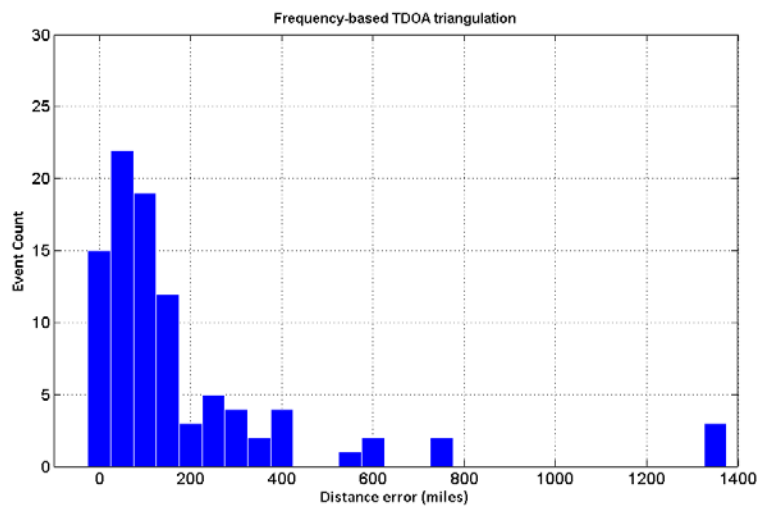


Fig. 2-41. Histogram of estimation results of Freq-based TDOA triangulation (2010-2011)

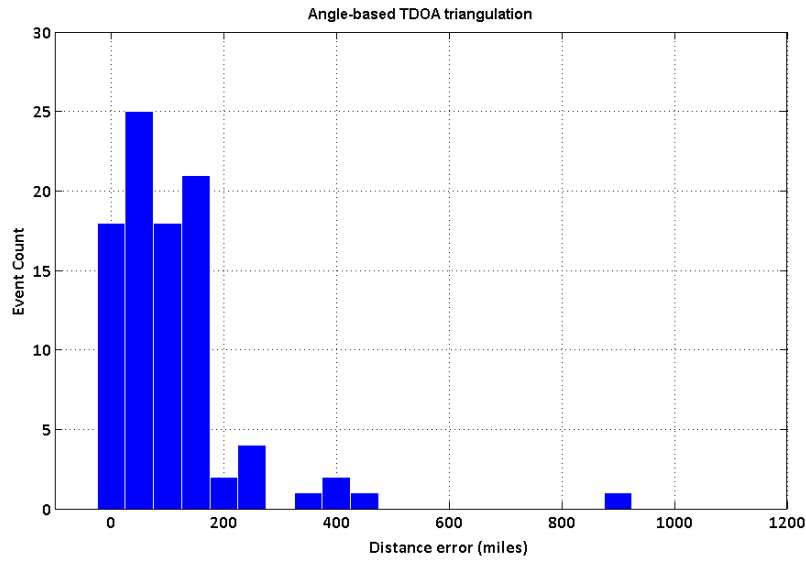


Fig. 2-42. Histogram of estimation results of Angle-based TODA triangulation (2010-2011)

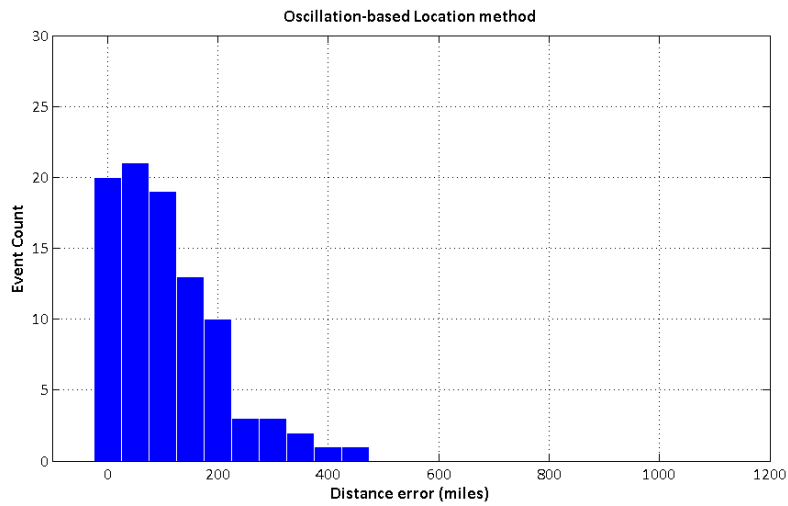


Fig. 2-43. Histogram of estimation results of Oscillation-based method with Angle data (2010-2011)

2.6.2 Load Shedding disturbance

For the load shedding disturbance, there is only a limited number of confirmed event cases (13 cases) from 2009-2011. The comparison of the estimation results with different location methods are listed in Table 2-3. Since the oscillation-based method only works for generation trip event, it is not evaluated with load shedding event cases.

Table 2-3 Comparison of location estimation results with different methods for load Shedding
(2009-2011)

Distance Error (miles)	Correct	Satisfactory	Acceptable	Unacceptable	Non- convergent	Average (miles)
	0	0~100	100~200	>200	--	
Angle-based TDOA Triangulation	8	1	2	2	0	82.88
Freq-based TDOA Triangulation	6	1	2	4	0	122.81

2.7. Summary

The approaches discussed in this chapter collectively serve the purpose of estimating the event location for generation trip or load shedding events in power system. The event location estimation algorithm is brought to a new level with the phasor angle measurement being used instead of frequency measurement. The primary method is the TDOA-based triangulation method in Sections 2.3-2.4, which in most cases will provides satisfactory estimation results. A prototype version of the angle-based TDOA event triangulation method has already implemented in the FNET server, and it is being tested and tuned.

The oscillation-based event location method in Section 2.5 targets on the generation trip events with oscillation associated. The oscillation-based method can work individually or be implemented as complementary to the TDOA-based triangulation method. However, it is believed that a dense FDR deployment is necessary for the oscillation-based method to get better performance, since only close-by unit will detect significant frequency oscillation.

Though the location errors could be caused by various factors, e.g. some noisy measurements, the difference between real electric distance and the geometric distance, limited FDR deployment in some areas, etc, the off-line testing in Section 2.6 shows that all these approaches in this chapter can provide satisfactory estimation results. And it also proves that the angle data can serve the purpose better than the traditional frequency data.

Chapter 3. FNET Event Monitoring and Reporting System

In the previous chapter, three important event monitoring components are introduced.

- Event Detection
- Event Type classification/Event amount estimation
- Angle-based event location estimation

Based on these necessary monitoring components, the FNET power system event monitoring and automatic event reporting system is constructed and enhanced with NERC Frequency Response Initiative (FRI) tasks included. The purpose of a sound event monitoring and reporting system is aimed for detecting events in real-time, recording complete event files, performing on-line event analysis, providing on-time event alerts and addressing detailed event information to improve power system situational awareness capability.

Fig. 3-1 demonstrates the framework of FNET event monitoring and reporting system. Basically this system contains three layers: event detection layer, automatic event analysis layer, automatic event reporting layer. This chapter will focus on the FNET system architecture design and implementation.

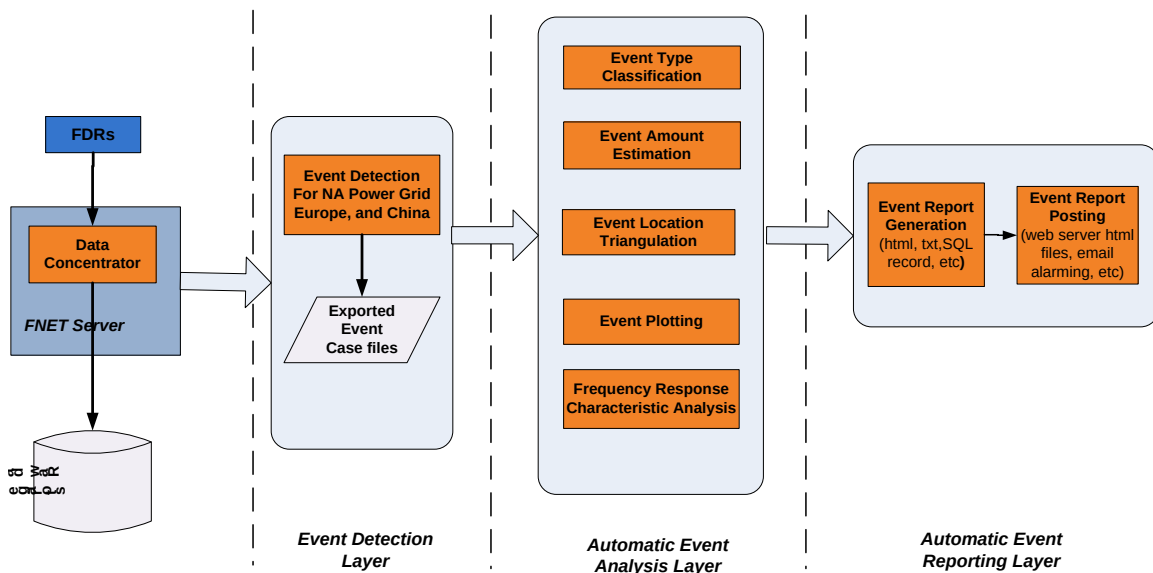


Fig. 3-1. FNET Event Awareness System

3.1. Event Monitoring

The FNET server continuously monitors the real-time data streams of FDRs distributed in North America, and other worldwide countries, e.g. Europe and China. The rate of average frequency change (df/dt) is chosen as an indicator of power system disturbance. The detail of event detection algorithm has been discussed in 2.1. Then the sound event monitoring system needs a well-designed event triggering mechanism, which is capable of capturing events in different synchronous power systems, and keeping complete event files automatically.

1) Multi-thread Event Trigger

The FNET event monitoring system covers North America (four interconnections, one individual power system in Oahu, HI), Europe and China. The event trigger in different synchronous power systems needs to be constructed in parallel, which means that one event being triggered in any single synchronous power system should not block event monitoring in another system. The multi-thread event monitoring structure is shown in Fig. 3-2. Each single thread will take care of event monitoring in one individual power system. And for each thread, different set of configuration parameters are applied, e.g. trigger threshold.

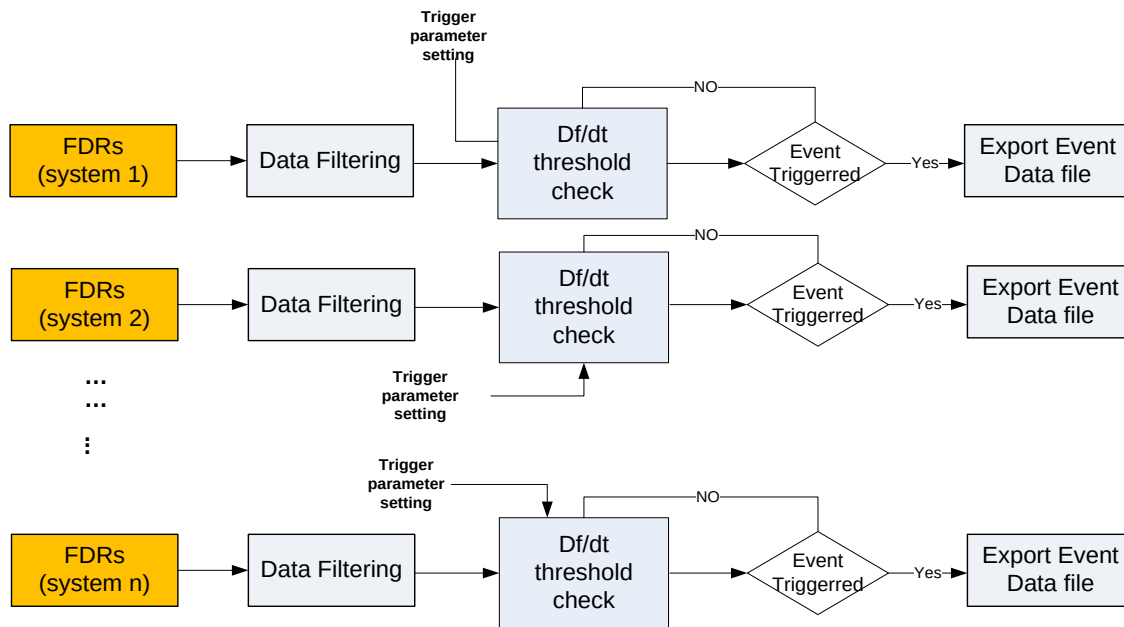
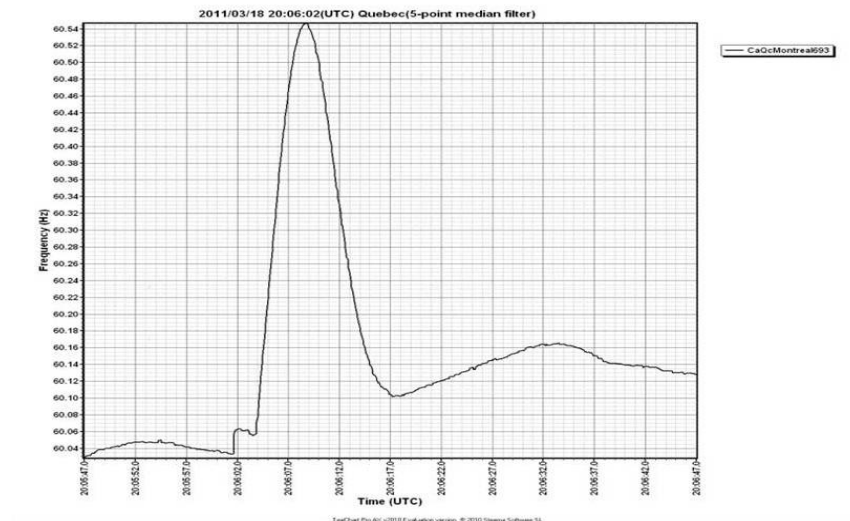


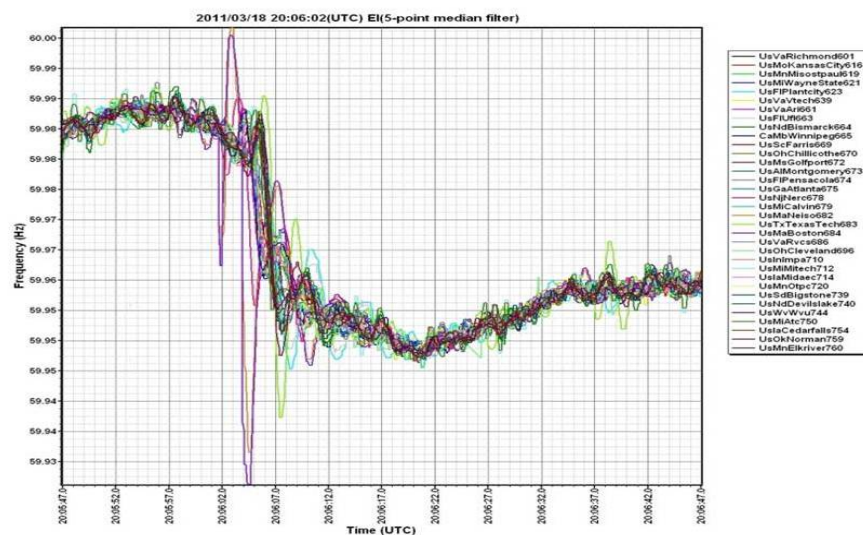
Fig. 3-2. FNET Multi-thread event monitoring system

Take the HVDC line trip between Quebec and New England area as example, which will trigger events in both Quebec and Eastern Interconnection at the same time. Depending on the power flow at the disturbance time, one Interconnection will detect it as load shedding, the other

as generation trip. Fig 3-3 shows the frequency plots of the EI and Quebec interconnection for the HVDC line trip disturbance on 03/18/2011.



(a) Load Shedding event detected in Quebec Interconnection



(b) Generation trip event detected in EI

Fig. 3-3. Frequency plot of HVDC Line trip near Quebec and New England area on 3/18/2011

2) Event Voting Mechanism

A voting mechanism is included in the monitoring system to avoid false alarming caused by abnormal outliers from some FDR unit. The voting mechanism means that only when more than one FDR in the same synchronous power system observe rate of frequency change over threshold, one event trigger will be reported. The required minimum number of FDRs can be adjusted. Fig 3-4 shows the flowchart of the event trigger procedure.

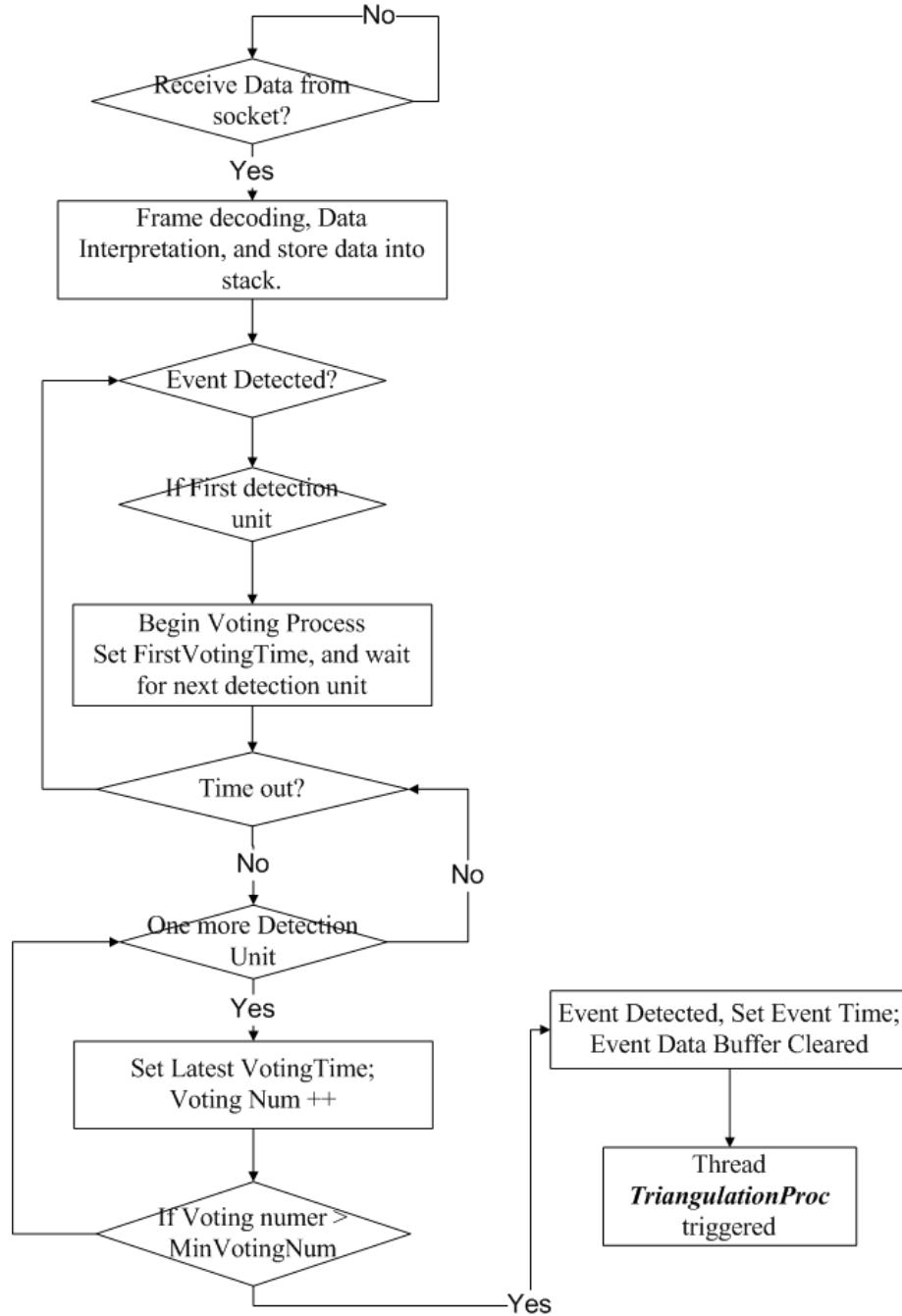


Fig. 3-4. Flowchart of Event Monitoring Procedure

3) Flexible Event Recording Mechanism

After one event being detected, a flexible time length of data will be automatically exported into TXT files. As a complete event record, the data length should cover the time period of before-, during- and post-disturbance. These TXT files are referred to as event case files. These event case files are critical components in the FNET file system, and they will be

further used as input to various FNET applications, e.g. event location estimation, event visualization, and other dynamic analysis modules.

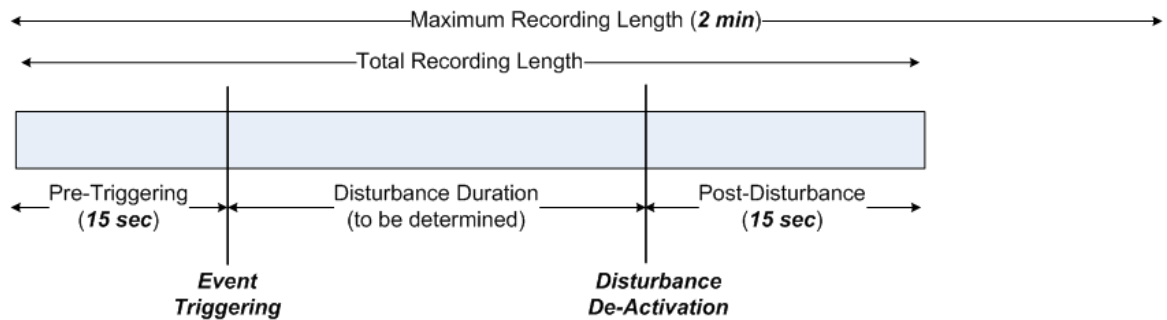


Fig. 3-5. Illustration of flexible event recording

The flexible event recording mechanism is shown in Fig. 3-5. The FDRs will initiate event data recording on the event triggering signal, and continue the recording for the fault duration period. The disturbance duration is deactivated by checking the rate of frequency change (df/dt), which means that the df/dt should return back to a pre-defined small range following the dramatic changes during transient period. And the post-disturbance data length is configurable, so is the pre-triggering data length.

So a complete event data recording length is determined by the pre-triggering data length, the disturbance duration length, the post-disturbance length, and the maximum recording length. Here the maximum record length is used to limit the event data file sizes, which is configurable. When the duration length is over the maximum recording length, the server will terminate the recording and output current existing buffer data into txt file.

3.2. Automatic Event Analysis

Fig. 3-1 lists the major functions of the automatic event analysis system, which includes:

- Event type classification, event amount estimation and event location estimation;
- Frequency Response Characteristics analysis (including point A/B/C frequency calculation, interconnection frequency calculation, median frequency calculation, minimum/maximum frequency trend calculation, etc);
- Event plotting

3.2.1 Frequency Response Characteristics Analysis

Frequency response is a measure of the collective ability of the synchronized generation and load in an interconnection to arrest and then stabilize rapid changes in frequency. It is measured by relating a change of the balance between load and generation (expressed in units of megawatts or MW) to the associated change to the settling frequency (expressed in units of 0.1 Hz). Traditionally, frequency response studies are focusing on measuring frequency arresting performance following events involving the sudden loss of a large amount of generation or load.

There is clearly a recognized need within the industry for consistent and automated reporting of the Frequency Response Characteristics (FRC) by the Balancing Authorities. The FNET wide-area frequency measurement before and after events enables an automatic analysis and report of frequency response characteristics associated with sudden loss of a large amount of generation or load.

An automatic FRC analysis module has been designed and implemented in FNET system. Some FRC can be automatically calculated in near real-time with interconnection frequency measurement from FNET system. The following discussion will deal with the point A, B, and C frequency calculation of power system disturbances.

3.2.1.1 Point ABC Frequency calculation

Referencing the North American Electric Reliability Corporation's (NERC) frequency response standard, the three characteristics points of interest are, as shown in Fig. 3-6:

- Point A: Interconnection frequency immediately before disturbance, typically close to 60Hz
- Point B: Interconnection frequency at the point immediately after the frequency stabilizes due to governor action but before contingent control area takes action.
- Point C: Point of maximum frequency excursion due to the loss of rotating kinetic energy from the interconnection.

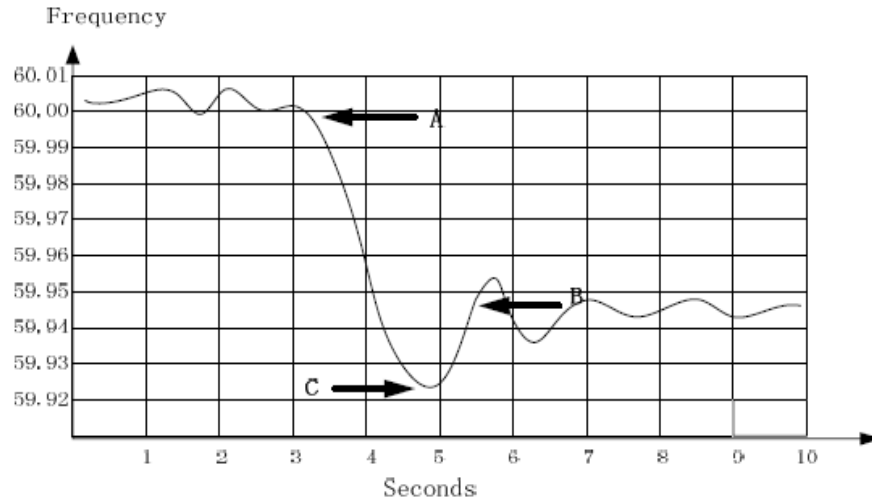


Fig. 3-6. Typical frequency excursion during frequency drop disturbance

In absence of a complete guidance on the calculation method of Points A, B, and C on FRC during this work, a fixed time window averaging mechanism is implemented here.

Instead of using any single FDR frequency measurement, we use the median value from all active FDRs' measurement as the interconnection frequency (the red solid line in Fig. 3-7) for point A, B, C calculation. And then for the initial frequency (Point A) (i.e., the frequency immediately prior to the event), the averaging period is the 15 seconds prior to the event. For the settling frequency (point B), the averaging period is 32 seconds, starting 20 seconds after the event time. The point C is the maximum frequency excursion point from 5 sec to 15 sec after the event time.

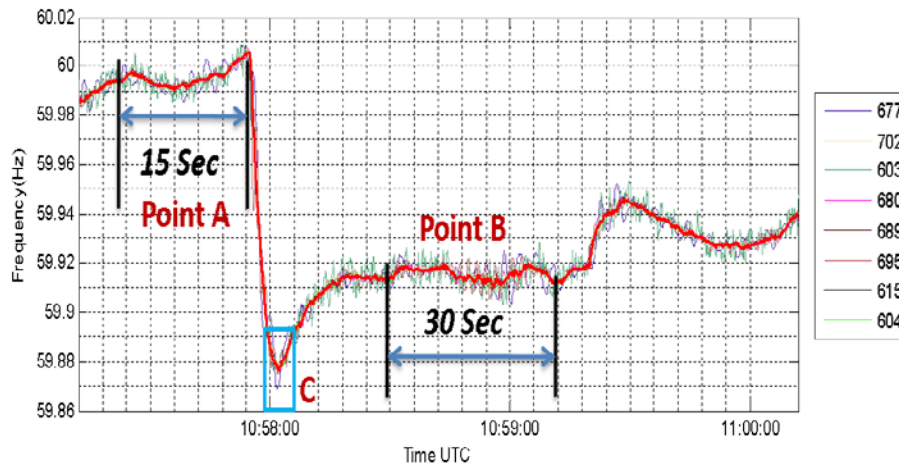


Fig. 3-7. Illustration of Point A,B, and C Calculation

Fig. 3-8 shows an example of Point A/B/C calculation of one generation trip in WECC.

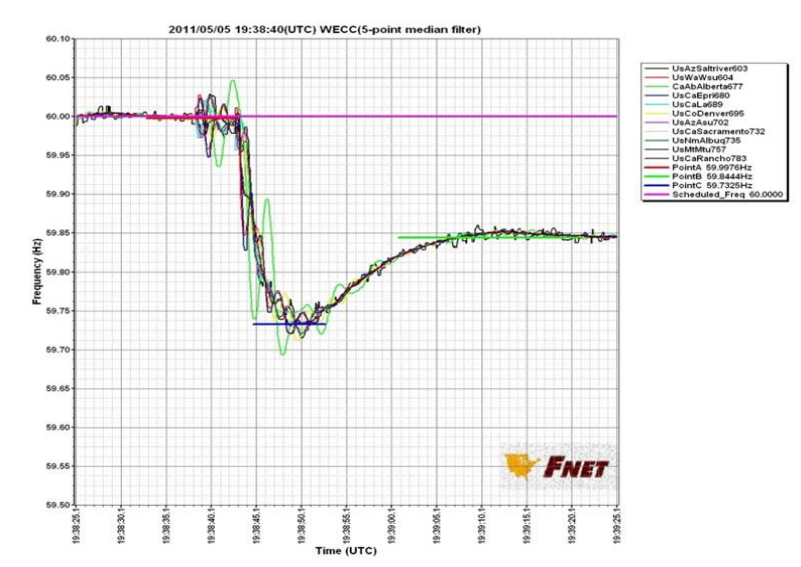


Fig. 3-8. Example of Point A,B, and C Calculation of generation trip on WECC

Although with the limitations imposed by the absence of data of the magnitude of net change between load and generation as well as ongoing improvements in methods used to measure the change in frequency, a complete FRC profiles cannot be achieved solely on the FNET wide-area measurement currently.

3.2.2 Event Plotting

The graphics serve as an intuitive way to present different time periods during power system disturbance, e.g. the pre-fault, post-fault, transient period, etc. Different types of frequency plot, phase angle plot and event location map have been designed and implemented to present system dynamics and event analysis results.

Fig. 3-9 illustrates some event frequency plot examples. Fig. 3-9(a) presents the frequency excursion from all FDRs, with point A/B/C frequency information marked. Fig. 3-9(b) shows the frequency excursion of the FDRs with earliest TDOA, which reveals the frequency propagation phenomenon. Fig. 3-9(c) shows the 20-min system frequency, which clearly shows the frequency recovery from a sudden loss of generation unit.



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3.3. Automatic Event Reporting

Upon detecting an event, the event analysis system retrieves event data of all FDRs, and extracts out useful event information. As the next step, the FNET server is designed to trigger the event reporting routine automatically.

The following figure shows the basic framework of the FNET event reporting system. The event reporting system focuses on the distillation of event analysis result into different reporting format and online information distribution. The generated event reports are intended for immediate online distribution and historical archive. The online event report distribution works in many ways, e.g. email, web-accessible html files, etc.

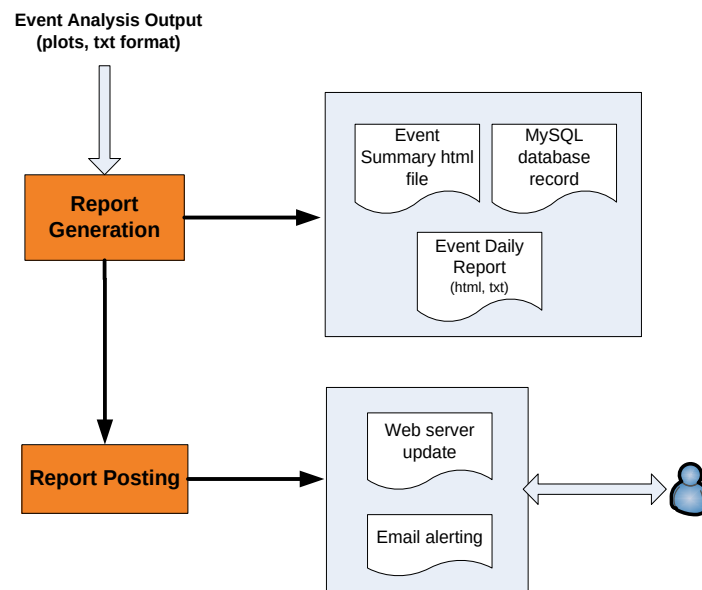


Fig. 3-10. The flowchart of FNET event reporting routine

Basically this event report is generated, and then sent out in email format and updated on FNET web server for web-accessing. The report will contain event analysis result (e.g. event type, event location, frequency response characteristics), and different types of event plots. And a daily summary of FNET frequency disturbances will also be generated and sent out in e-mail format on a daily basis.

Chapter 4. Real-time Visualization of Wide-Area Angle Measurement

4.1. Introduction

In many state-of-art works related to power system applications on synchrophasor measurements, researchers have realized the importance of developing high quality visualization tools to interpret power system states such as frequency, voltage magnitude, phase angle, and angle differences [42]-[47]. The visualization types include diagrams, pie charts, color contours, animations, etc.

In light of this, in the FNET system several visualization tools have been developed to interpret the power system situation and improve situational awareness in an intuitive way. These tools correlate the FNET wide-area measurements with corresponding FDR geographical information, then present in different graphic formats.

These visualization tools can be categorized into two basic types: one is the non-real time event playback with frequency or angle measurements; the other is the real-time visualization of FNET wide-area frequency and angle measurement. Effective real-time visualization plays an increasingly important role in interpreting the massive data available to the power system engineers. The real-time frequency gradient map has been developed and implemented since 2007; In order to visualize the power system from the phase angle aspect, a real-time angle visualization framework is proposed and implemented in FNET server that correlates the real-time wide-area angle measurements with their geographical information, and displaying these measurements as 2-D colored surfaces over the EI map.

4.2. Framework of Real-time Angle Visualization

The real-time angle visualization framework has four major components shown in Fig. 4-1.

- Real-time angle measurement storage
- Angle-data conditioning and calibration
- VTK-based angle contour map rendering and movie generation
- FNET Server visualization web service

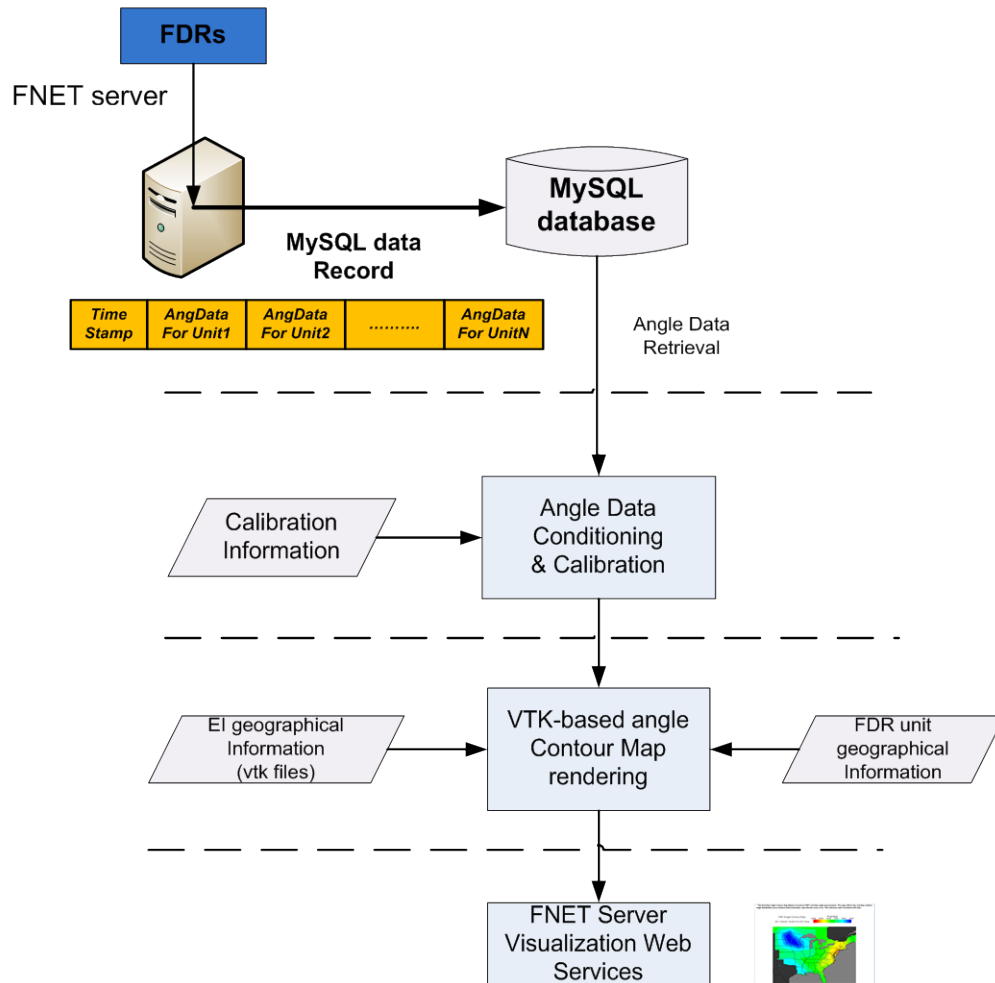


Fig. 4-1. Framework of Real-time Angle Visualization

4.2.1 Angle Measurement Storage

To be different from the power system disturbance playback which takes the event files as data input, the real-time visualization needs to retrieve real-time measurement data from server. The FNET server is designed to receive data from each FDR and save it. There are two factors being taken account of during data storage for angle or frequency real-time visualization.

1. Data Down-sampling

The original data sample rate of each FDR is 10Hz. During quasi-steady state, there are no abrupt fluctuations for frequency or relative angle measurement. It is not necessary to render the angle or frequency contour map at this high rate. Furthermore, in order to reduce the image rendering burden, the input data rate for real-time visualization is reduced. Currently the frame rate of 4sec/per frame is adopted.

2. Data Synchronization

Considering the different time delays of data from different FDRs, mostly caused by the Internet transmission delay, the frequency or angle measurement needs to be time aligned firstly. So a data buffer is created in server for time synchronization. And then after time synchronization, a time-aligned data record will be created and inserted into MySQL database. The following data processing module will retrieve the latest data record out of MySQL database for further application.

4.2.2 Angle Data Conditioning & Calibration

The angle data record retrieved from MySQL database is the raw phase angle data directly sent by FDR to FNET server. Before the raw phase data being sent into VTK-based visualization module for graph rendering, data conditioning and calibration need to be performed first, as shown in Fig. 4-2.

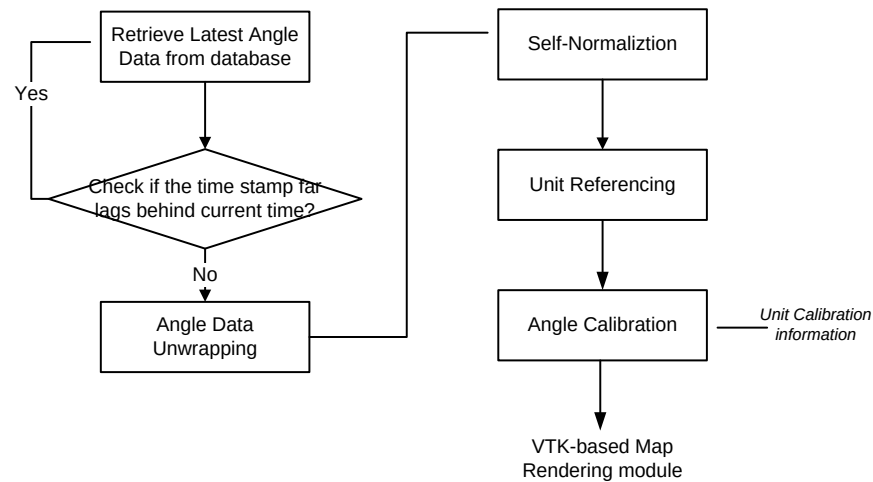


Fig. 4-2. Flowchart of Data Processing for angle real-time visualization

1. Angle data conditioning

The raw phase angle data will go through the same data conditioning procedure as discussed in Section 2.3.2, e.g. angle data unwrapping, self-normalization, taking reference to some unit.

2. Angle Data Calibration

Since there exists phase shift from the high voltage transmission line to 120 V distribution level, a calibration process needs to be taken to calibrate the FDR angle measurement to present a nearby high-voltage transmission line roughly. In other words, some values will be added onto the FDR angle measurements. The calibration parameter is obtained through EMS

(Energy Management System) angle measurement data on high voltage transmission lines. The calibration process is described as follows:

- 1) Identify the FDR locations on Eastern Interconnection grid map, and find one closest high-voltage transmission line for each FDR;
- 2) Find the angle measurement of these high-voltage transmission lines from EMS data;
- 3) Pick up one high-voltage line as reference, and calculate the relative angle this reference line using EMS angle measurement. If some high-voltage transmission line is picked as reference, the closest FDR to this reference transmission line is also chosen as reference unit for the FDR relative angle calculation.
- 4) Take these relative angles in EMS as angle calibration parameter for corresponding FDR.

The calibration parameter obtained from the above steps for each FDR is just a rough estimation. However, it will make the FDR angle measurement taken at the distribution level more sense to present the practical power system operation status. One example of the angle contour map of Eastern Interconnection after calibration is shown in Fig. 4-6. The angle distribution on the map makes sense that the eastern coastline area presents as power sink with massive load demanding.

4.2.3 VTK-based Angle Visualization Module

As the main part of this real-time visualization framework, this module is developed with the Visualization Toolkit (VTK), which is open-source software for computer graphics, image processing and visualization [48]. And it also supports a wide variety of visualization algorithms, including scalar, vector, texture, etc. VTK includes a C++ class library; the implementation of the library has been strongly influenced by object-oriented principles. C++ has obvious advantages over Matlab in real-time application in the aspect of processing speed. Furthermore, the FNET server system is developed in C++, considering the compatibility possibility, it is better to keep using C++ as programming language.

In VTK, a visualization project is executed through a 'pipeline', which is a sequence of different processing methods that operate on different types of data objects to finally generate geometry that can be rendered by the graphics engine. The pipeline execution model is shown in Fig. 4-3. Firstly, the source data, e.g. the angle measurement, are represented with datasets, then processed by filters, and mapped to graphics with mappers. A dataset is a data object with

structure that consists of cells (e.g., polygons, lines), points (x-y-z coordinates), etc. [48]. The FNET angle visualization module follows the ‘Pipeline’ execution procedure in VTK to render an angle contour map using real-time measurement.

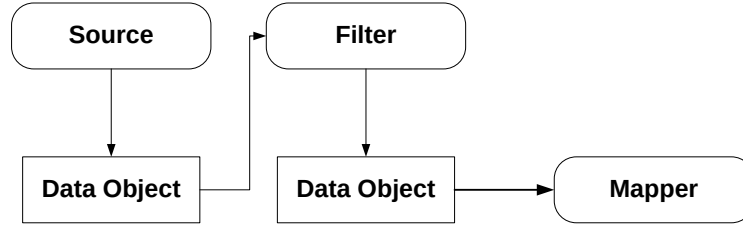


Fig. 4-3. The pipeline execution models in VTK

The visualization module consists of two main parts: 1) obtain FDR measurement data and form interpolation matrices, 2) angle contour map rendering.

1. Data Matrix Generation

The flowchart of data matrix generation is shown in Fig. 4-4. The rendering area (EI area) is divided into $N \times M$ small mesh grids where N and M are the number of divided sections along the longitude and latitude, respectively. The size (N , M) can be adjusted. The angle scalar value for each small mesh grid can be estimated by interpolating angle measurements from limited number of FDR units. One instance of VTK data object *vtkPolyData* is used to represent the interpolated point locations and their scalar values.

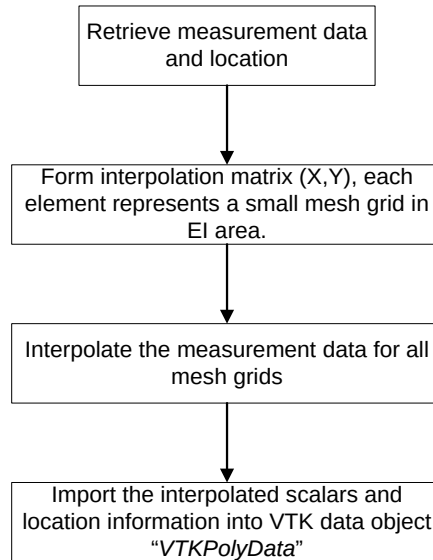


Fig. 4-4. Flowchart of generation of measurement matrices of map rendering

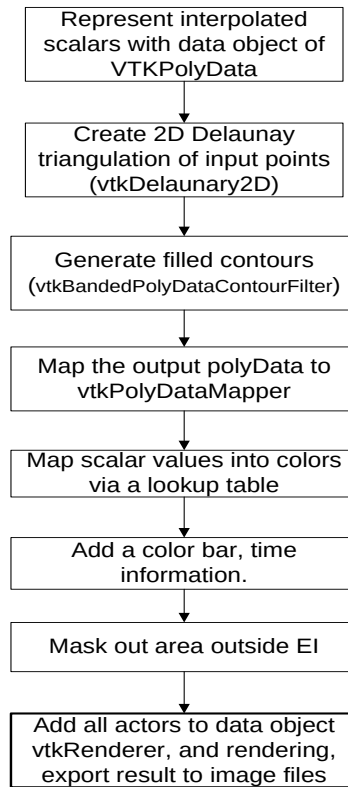


Fig. 4-5. Flowchart of Angle Contour Map Generation

2. Angle Contour Map Generation

The flowchart of angle contour map rendering is shown in Fig. 4-5. The interpolated points with scalar are filtered to certain geometric structure (e.g. contour filter), then mapped onto VTK object vtkPolyDataMapper. These geometries (lines, points, etc.) are mapped into different color through a predefined lookup table. Finally these mapping results are added into a render window and rendered. The rendering angle contour map is shown in Fig. 4-6.

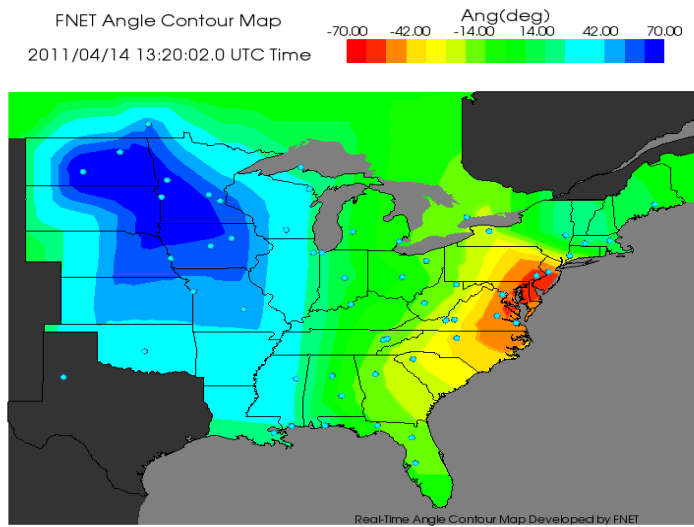


Fig. 4-6. Example of Angle Contour Map

3. Automatic Movie Generation

Besides exporting the rendered contour map into an image file, the VTK-based angle visualization module is also exporting the angle contour map into an Audio Video Interleave (AVI) file along the time axis. The animation movie is saved every 30 minute. The frame rate is 20 sec per frame. Both the angle contour map and angle animation movie are available as part of FNET visualization web services.

4.2.4 FNET Visualization Web Service

The angle visualization functions are uploaded into the FNET server, and accessible through the FNET web services in two ways: real-time angle contour map display refreshing every 4 sec; and angle contour playback of recent time window (e.g. 30 mins).

1. Real-time Angle Contour Map

The FNET web server provides web-accessible real-time visualization of wide-area frequency or angle measurement. Currently the angle contour map only covers the eastern interconnection. Fig. 4-7 shows the snapshot of an angle contour map. The webpage script is designed to refresh every 4 sec, retrieve the newly-updated angle contour map on web server, and display it. As indicated in Fig. 4-7, the area with negative angle value indicates the power sink.

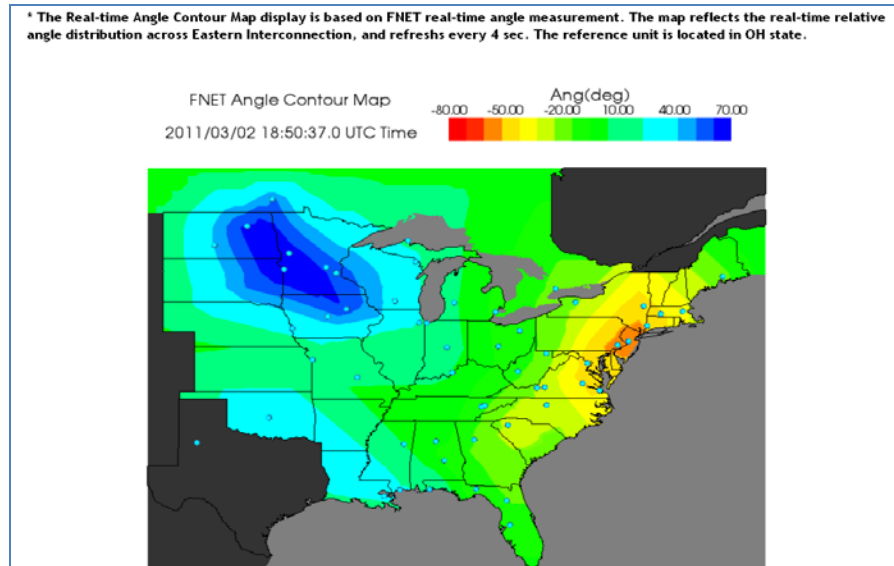


Fig. 4-7. Screen shot of FNET real-time angle contour map display

2. Historical angle animation movie playback

Each angle playback animation movie covers 30-min length of angle fluctuation under quasi-steady status. The recording rate is one frame per 20 sec. The animation playing rate is one frame per 0.5 sec, so the each angle playback movie lasts 45 sec.

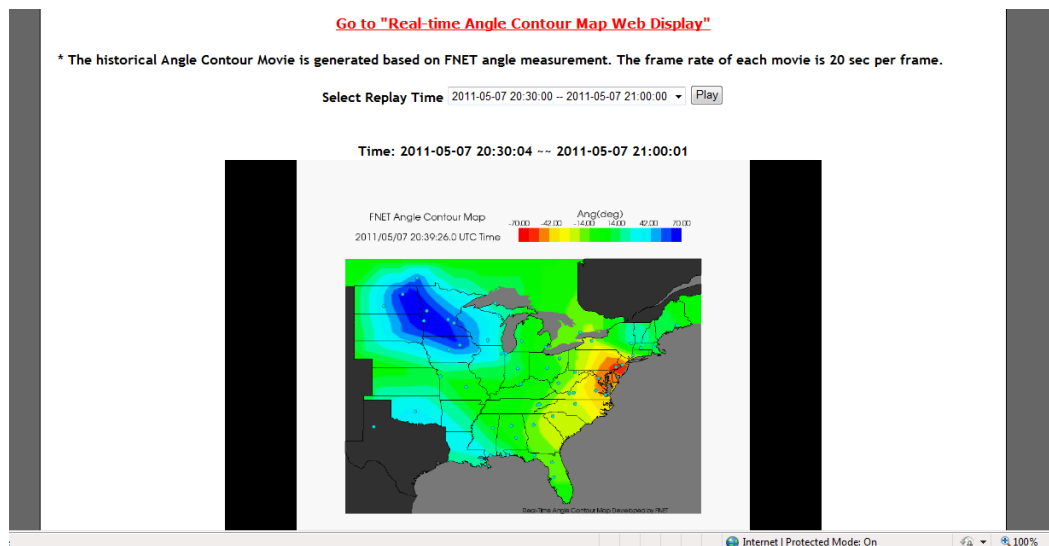


Fig. 4-8. Screen shot of FNET historical angle animation playback.

Chapter 5. Statistical Analysis of Power System Disturbances in Worldwide Power Grid

The FNET system has been monitoring North America power grid since 2006, it has successfully identified a lot of generation trip-like or load shedding-like disturbances [8]. As a successor of the statistical analysis of frequency disturbances before Jan, 2008 in [5], the statistical characteristics of frequency disturbances captured by FNET system are further analyzed and compared across different interconnections in NA power grid from 2008 to 2011. The statistical analysis and comparison only cover disturbances in EI and WECC system. These analyses will help us to understand power grid's performance and trends over time.

And with the recent FDR deployment in some other worldwide countries, e.g. Europe, China, South Korea, etc., typical frequency response characteristics of the generation and load loss events are analyzed in Europe, and compared with North America power grid. What is found here could serve as the first step to the application of FNET to global power systems.

5.1. Statistical Analysis of Disturbances in North America Power Grid

5.1.1 Disturbance Selection

As discussed in Section 2.1, the FNET event detection module monitors and treats the rate of frequency change (df/dt) as an indicator of frequency disturbance. A threshold for the rate of frequency change is set to capture frequency disturbances at the first step, and then the FNET event monitoring system is set to filter out those disturbances with trivial power mismatch. The power imbalance estimation is discussed in Section 2.2. The power imbalance threshold is 400MW in EI and 330MW in WECC.

The power system disturbances are categorized into generation trip-like or load shedding-like events in the FNET system. The basic information of the FNET frequency events from Jan, 2008 to Sept, 2011 is listed in Table 5-1.

As shown in Table 5-1, the number of events in ERCOT is much smaller than the other two, since there is only a limited number of FDRs deployed in the ERCOT system and the data continuity of some FDR units cannot be guaranteed, which greatly affect the disturbance

observability in the ERCOT system. So only the disturbances statistics from 2008 to 2011 in the Western and Eastern Interconnection is investigated in this chapter.

Table 5-1 The number of frequency disturbances in North American Power Grid (2008-2011)

Interconnections	Event Type	2008	2009	2010	2011 (Up to Sept)
Eastern Interconnection	Generation Trip	318	339	455	352
	Load Shedding	174	141	567	480
	Total	492	480	1022	832
Western Interconnection	Generation Trip	86	167	177	145
	Load Shedding	43	53	224	174
	Total	129	220	401	319
ERCOT	Generation Trip	45	35	152	71
	Load Shedding	3	0	3	2
	Total	48	35	155	73

5.1.2 Statistical analysis of frequency disturbances by time

5.1.2.1 Eastern Interconnection

Fig. 5-1-Fig. 5-3 shows statistics analysis of frequency disturbances in Eastern Interconnection from Jan, 2008 to Sept, 2011. The statistical distributions of power system disturbances by day, by hour, and by month are given in each year separately. Several conclusions can be drawn:

1. The number of load shedding-like disturbances keeps increasing yearly from 2008 to Sept, 2011 in the FNET system as shown in Table 5-1.
2. As shown in Fig. 5-1, the generation trip-like disturbances are evenly distributed throughout the whole year by month in general. The load shedding-like disturbances are more likely to occur in April and May.
3. During a day, load shedding-like events are more likely to occur in 8:00-12:00 UTC in Eastern Interconnection (Fig. 5-3), which is around 3:00~7:00 EST in the early morning locally. In most cases, pump storage units shutting down appear as load shedding. The turn-off operation of most pumps storage units usually happen in the early morning locally.
4. During a day, the occurrence of generation trip-like disturbances is more evenly distributed than load shedding-like disturbances by hour (Fig. 5-3). In the EI system, generation

loss-like disturbance is slightly likely to occur in 18:00-20:00UTC, which is early afternoon locally.

5. During a day the peaks of the number of disturbances appear between 10:00-12:00UTC in EI (Fig. 5-3). This coincides with the peaks of load shedding-like disturbances.

6. When looking into the disturbance distribution by day in Fig. 5-2, the disturbances are almost evenly distributed throughout the week from 2008 to Sept, 2011.

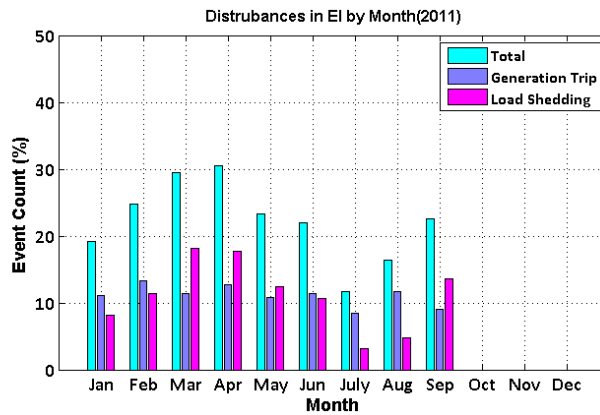
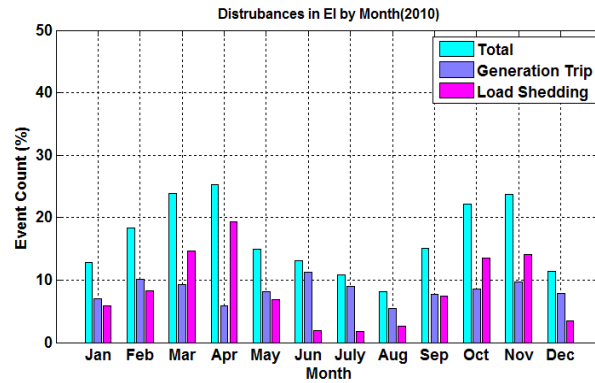
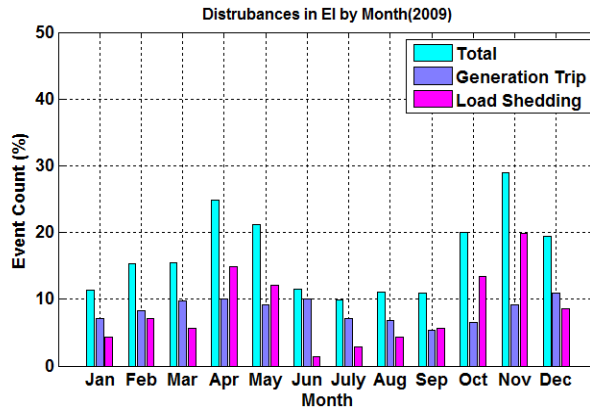
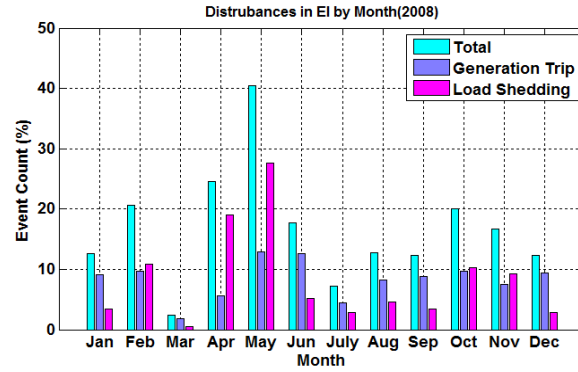


Fig. 5-1. Distribution of Frequency disturbances in EI by month from Jan, 2008 to Sept 2011

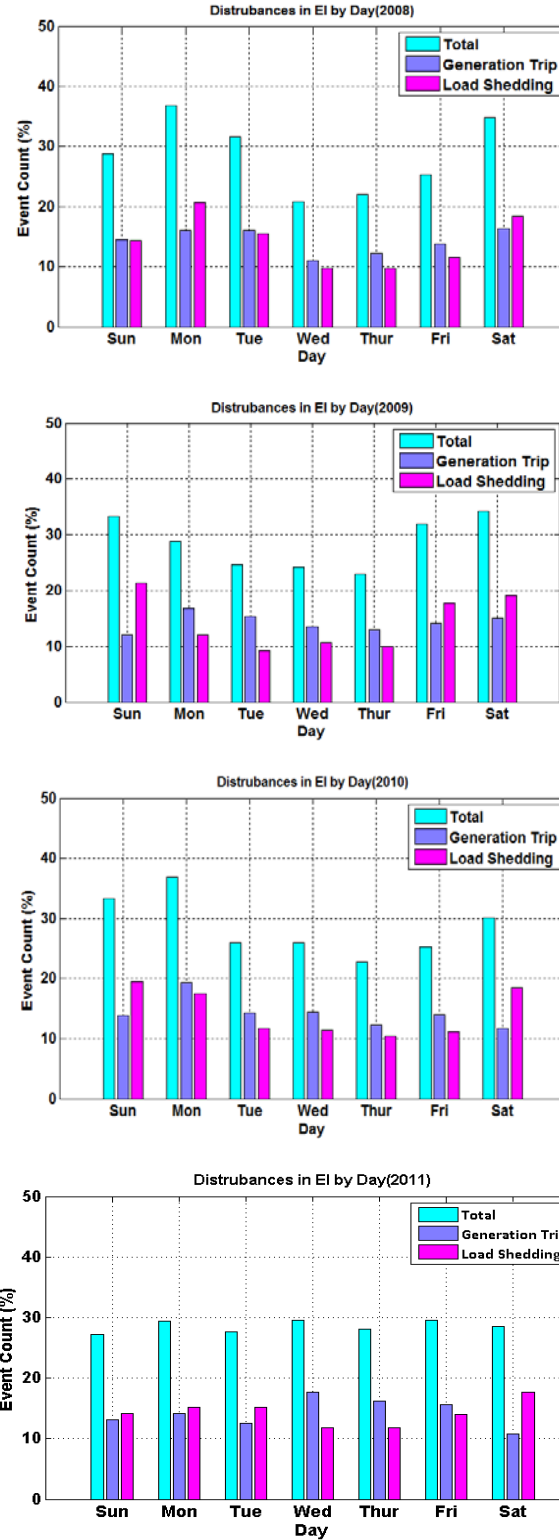


Fig. 5-2. Distribution of Frequency disturbances in EI by day from Jan, 2008 to Sept 2011

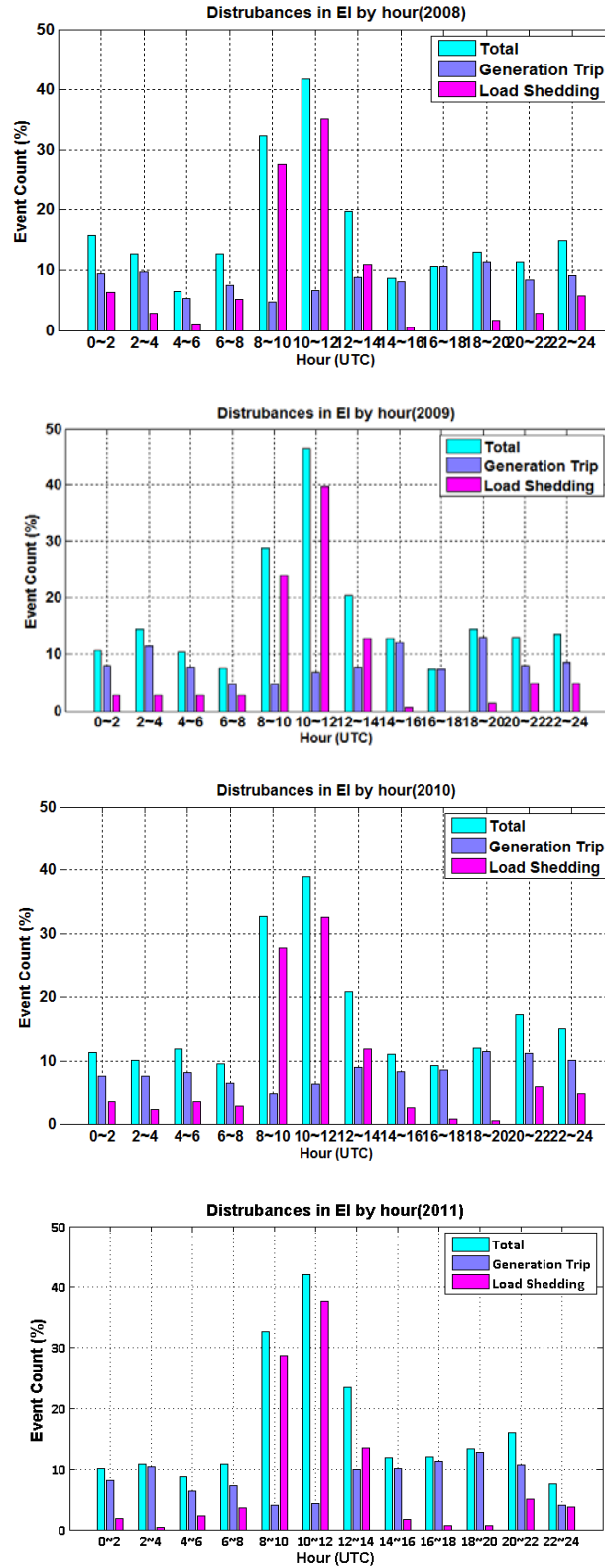


Fig. 5-3. Distribution of Frequency disturbances in EI by hour from Jan, 2008 to Sept 2011

5.1.2.2 Western Interconnection

Fig. 5-4 - Fig. 5-6 shows statistics analysis results of frequency disturbances in Western Interconnection yearly from Jan, 2008 to Sept, 2011. The statistical distributions of power system disturbances by day, by hour, and by month are given separately. Several conclusions can be drawn:

1. The number of load shedding-like disturbances also keeps increasing yearly from 2008 to Sept, 2011 in WECC, as shown in Table 5-1. From 2010, a significant increase in the number of load shedding-like disturbances is observed compared with generation drop-like disturbances. And the load shedding-like disturbances are more likely to occur in summer, from May to July (in Fig. 5-4).

2. During a day, the occurrence of load shedding-like events are clustered between 10:00-16:00 UTC in WECC (in Fig. 5-6), which is around 2:00~8:00 PST in the early morning locally. In most cases, pump storage units shutting down appear as load shedding. Nearly the same pattern is observed in EI, as discussed in Section 5.1.2.1.

4. During a day, the occurrence of generation trip-like disturbances is more evenly distributed than load shedding-like disturbances by hour (in Fig. 5-6). The generation loss-like disturbance is slightly likely to happen in 16:00-22:00UTC, which is 8:00 to 14:00 PST locally.

5. When looking into the disturbance distribution by day in Fig. 5-5, the disturbances are almost evenly distributed throughout the week.

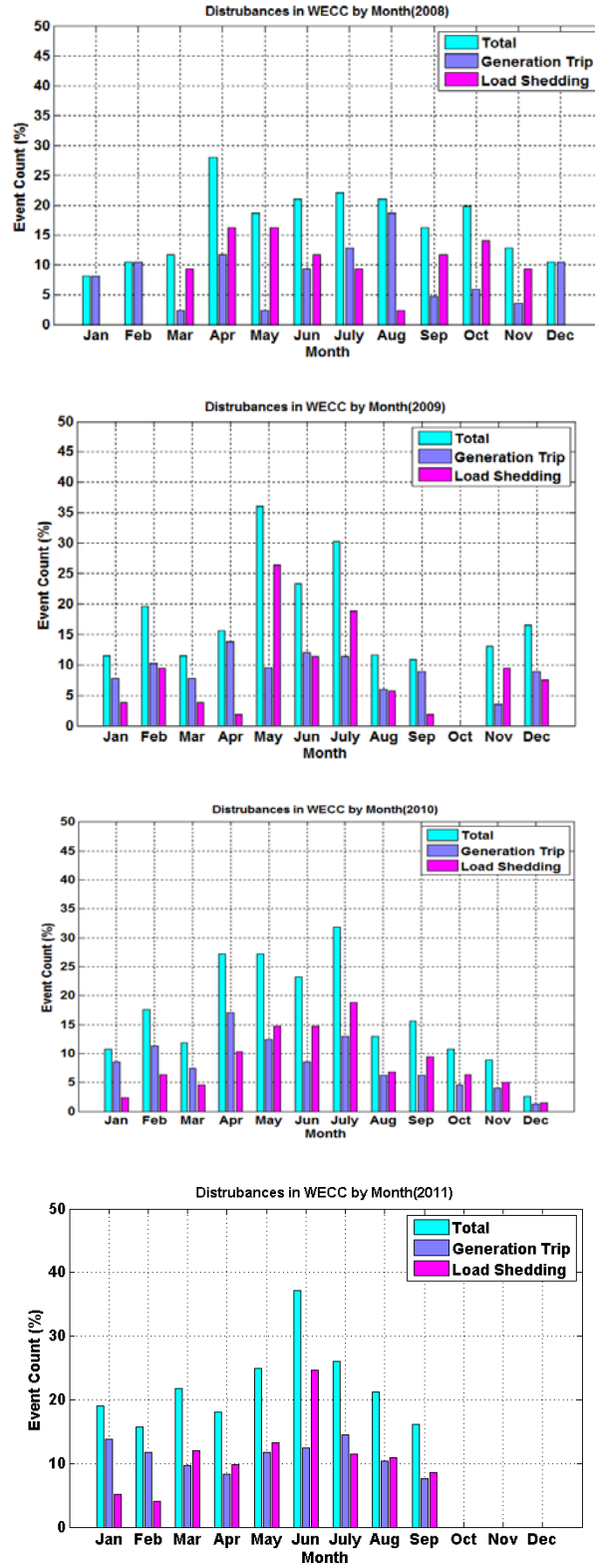


Fig. 5-4. Frequency disturbances in WECC by month from Jan, 2008 to Sept 2011

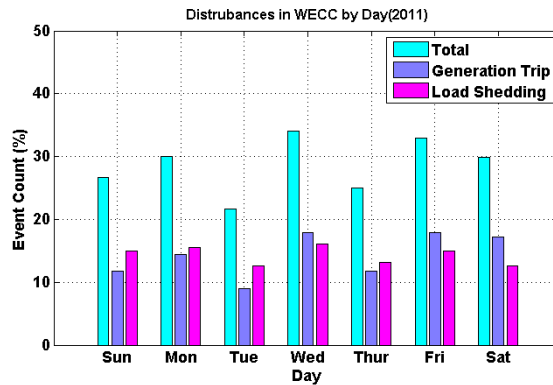
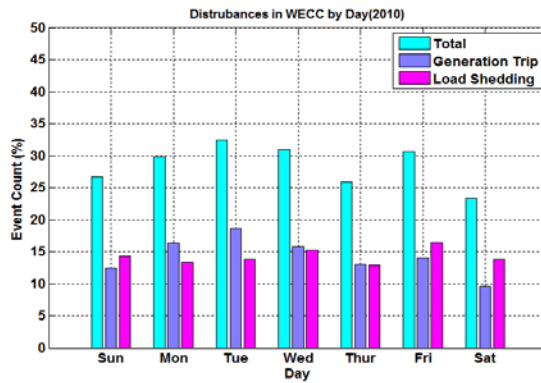
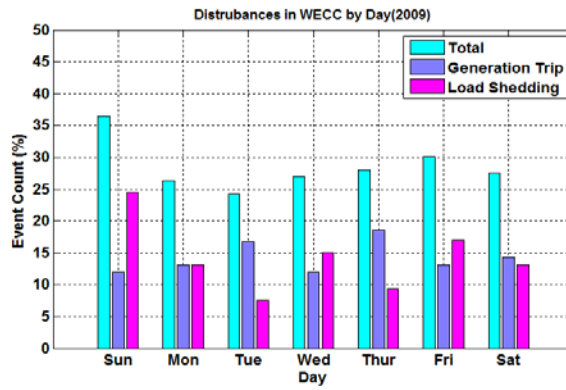
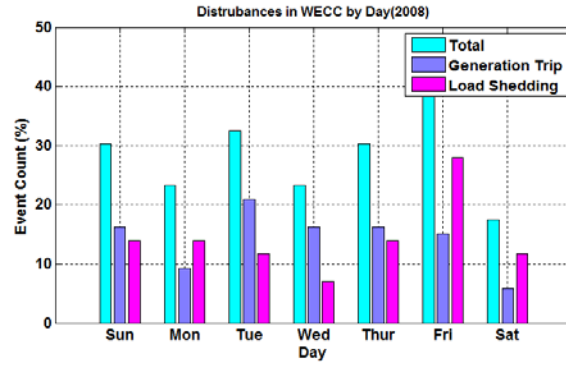


Fig. 5-5. Frequency disturbances in WECC by day from Jan, 2008 to Sept 2011

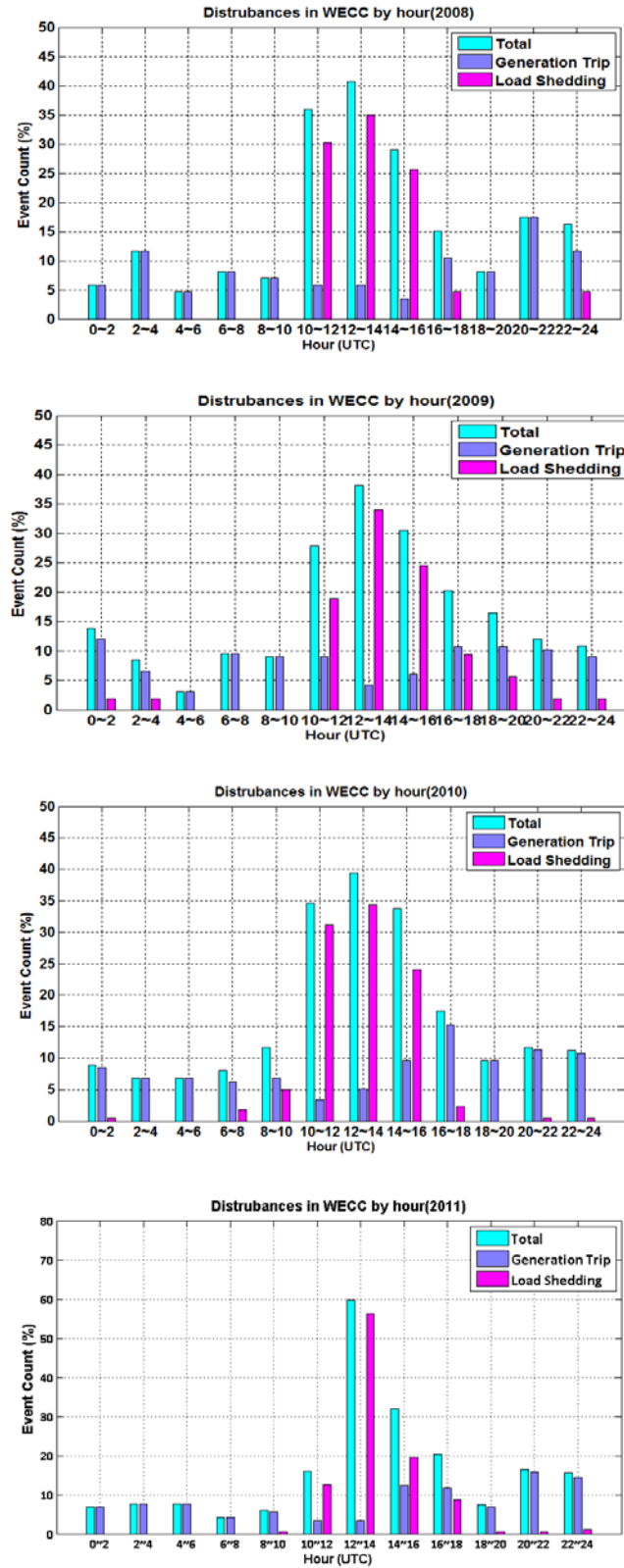


Fig. 5-6. Frequency disturbances in WECC by hour from Jan, 2008 to Sept 2011

5.1.3 Statistical analysis of power system disturbance by power mismatch

Fig. 5-7 and Fig. 5-8 show the statistical distributions of frequency disturbances by FNET power mismatch estimation yearly from Jan, 2008 to Sept, 2011 in EI and WECC. Several conclusions can be drawn:

1. Most of the disturbances in the EI system are detected with the power mismatch lower than 900MW. In the WECC system, the power mismatch of most disturbances is below the 700MW level. The difference between the EI and WECC system is probably caused by the total capacity difference between the two interconnections.

2. Few of load shedding-like disturbances are detected with amount higher than 700MW in EI and 500MW in WECC. The majority of the load shedding is associated with shutdown of pump storage plants. And the pump storage plants usually have relatively small capacities compared with generation plants.

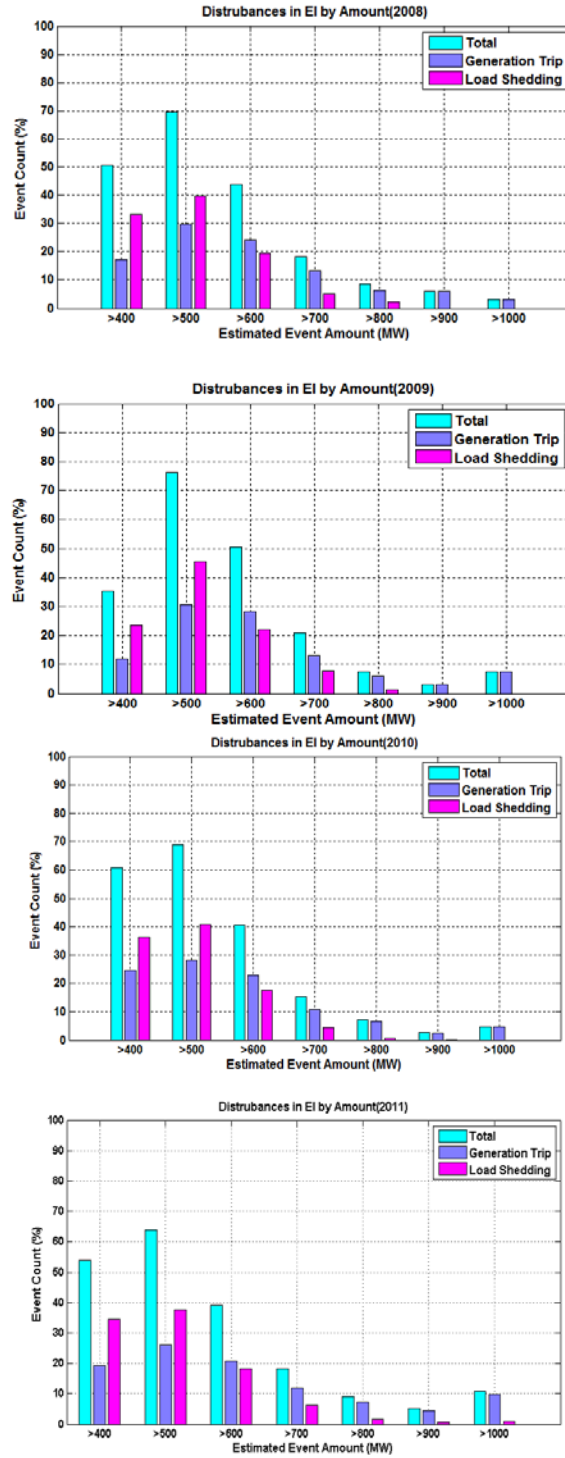


Fig. 5-7 Distribution of frequency disturbances by estimated power mismatch in EI from Jan 2008-Sept,2011

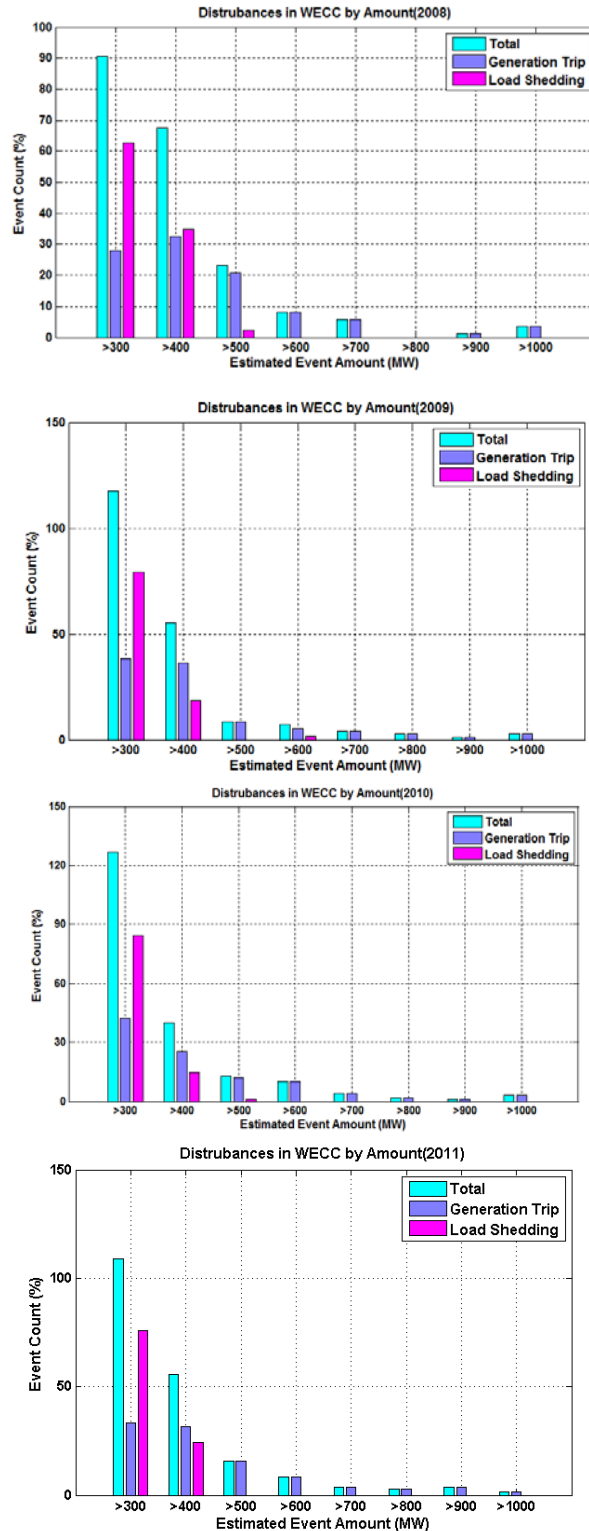


Fig. 5-8 Distribution of frequency disturbances by estimated power mismatch in WECC from Jan 2008-Sept,2011

5.2. Statistical Analysis of Disturbances in Europe Power Grid

The FNET event monitoring system has proved its effectiveness in triggering different types of power system disturbances in North American power grid. With the recent FDR deployment in the worldwide areas, e.g. Europe, China, Korea, etc, a trial event monitoring system over worldwide power grid is being set up on the FNET server. The feasibility and effectiveness of the FNET worldwide monitoring system is discussed in the section, taking the European power grid as an example. The analysis and comparison of different types of disturbances is included.

5.2.1 Europe Power Grid and FDR Deployment

With respect to the European power grid, each European country typically has their transmission system operators (TSOs) that operates their power system and makes sure that certain generators in the system meet reserve needs. These TSOs have made an association called ENTSO-E (the European Network of Transmission System Operators for Electricity), which represents 41 transmission system operators (TSOs) from 34 European countries [48]. Within the ENTSO-E there are 5 synchronously interconnected systems, including Continental Europe, Nordic, Baltic, UK and Ireland, as shown in Fig. 5-9.

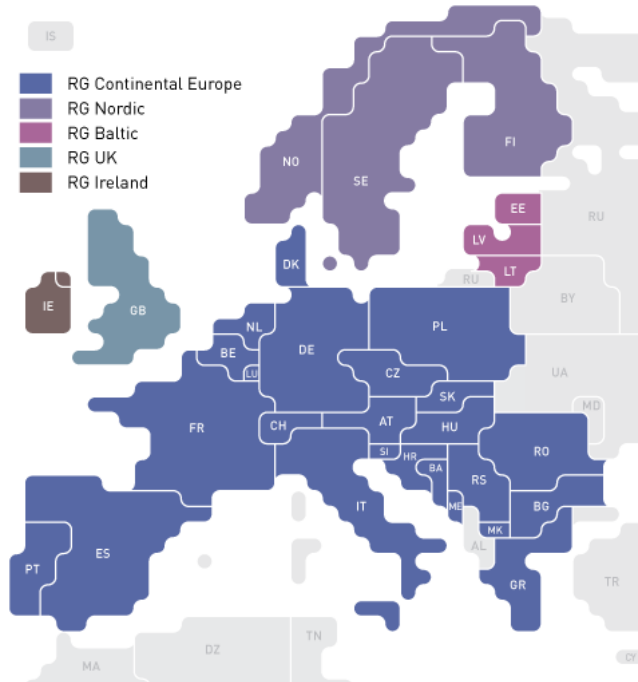


Fig. 5-9. Europe Power Grid (Courtesy to ENTSO-E[48])

Up to Sept, 2011, The FNET system has the FDR deployment in Continental Europe and Nordic system. The following table only lists those active FDRs in Europe.

Table 5-2 FDR Name and Location Information in Europe

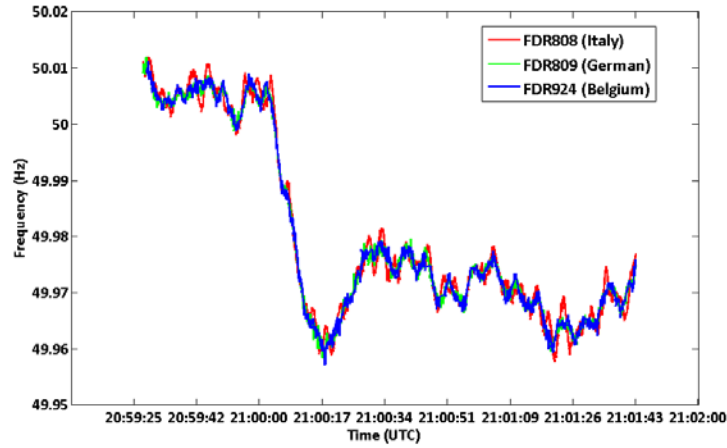
FDR Name	Location	Interconnection
FDR809	German	Continental Europe
FDR809	Italy	Continental Europe
FDR1009	Italy	Continental Europe
FDR924	Belgium	Continental Europe
FDR807	Sweden	Nordic

5.2.2 Typical Frequency Excursions of Disturbances in Europe power grid

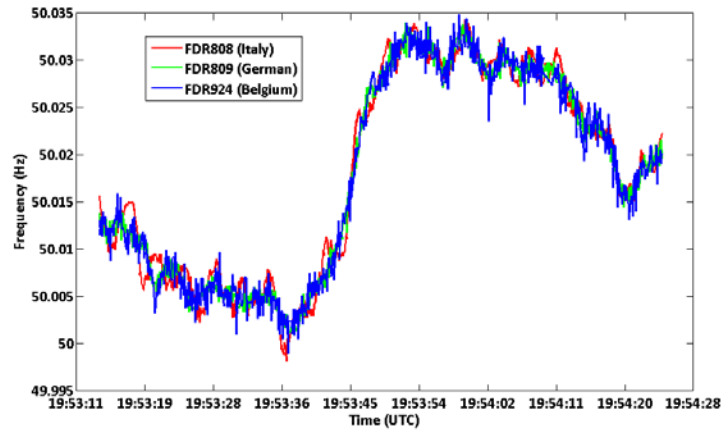
The FNET system monitors the European power grid based on the continuous data streaming from FDRs deployed in Europe. With proper threshold setting, the generator-trip like or load-rejection like frequency disturbance is being detected and reported in the FNET system. Considering current FDR deployment in Europe, only the frequency disturbances in Continental Europe and Nordic system are examined.

5.2.2.1 Continental Europe

The Net generation capacity of Continental Europe is around 660GW (end 2009) [48], which is comparable to Eastern Interconnection. An event trigger threshold close to the EI system is applied for the preliminary frequency event monitoring of Continental Europe, which is 0.0035Hz/sec as the df/dt threshold. For the generation capacity mix in Continental Europe, the fossil fuels constitutes more than 50%, the Nuclear constitutes about 20% [48]. The frequency characteristic greatly depends on the control setting of these generators. Fig. 5-10 demonstrates two types of frequency disturbances detected by the FNET system in Continental Europe. The measurements from the three FDRs synchronize with each other.



(a) Generation Drop-like



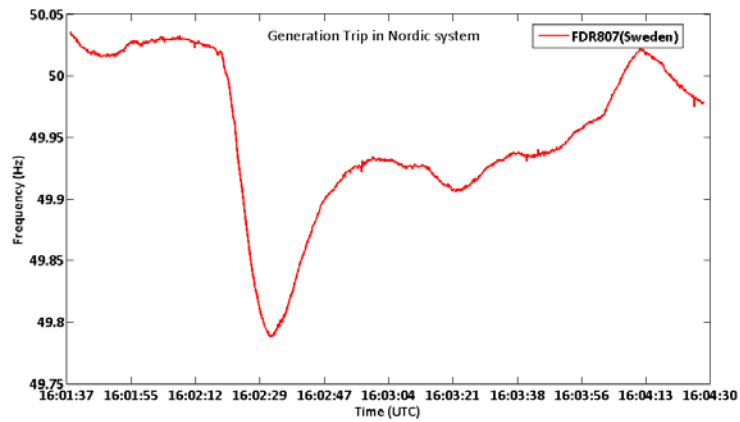
(b) Load Shedding-like

Fig. 5-10. Frequency disturbances in Continental Europe: (a) Generation Drop-like (b) Load Shedding-like

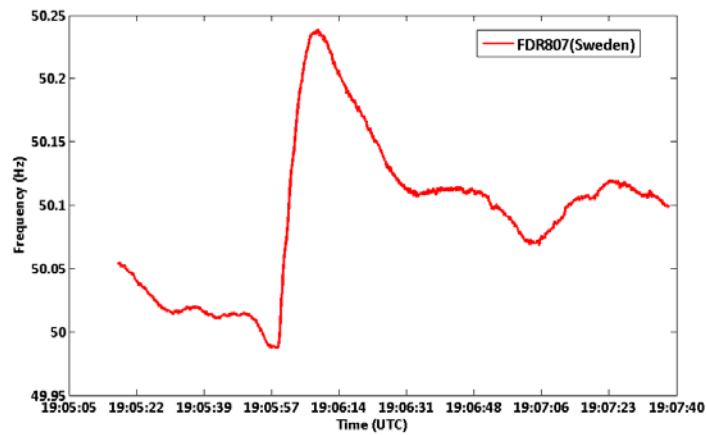
5.2.2.2 Nordic

The net generation capacity of Nordic is around 97GW (end 2009) [48], comparable to ERCOT [49]. A threshold similar to the ERCOT system is applied for Nordic system, which is 0.008Hz/sec for df/dt threshold. For the generation capacity mix in Nordic system, the Hydropower constitutes most part, nearly 58%, the nuclear power takes up about 20% [48], which differs a lot from the ERCOT system for which the Natural gas and coal constitutes major parts [49]. Fig. 5-11 demonstrates frequency responses of Nordic system to different types of disturbances captured by the FNET system. Compared with Fig. 5-10, the frequency responses of both generation drop and load shedding disturbance in Nordic system see a much quicker frequency recovery following transient periods, which is probably caused by the significant frequency governing from hydro powers [50]. In the North American Hydro-Quebec power system, a quick frequency recovery can also be observed, due to more than 90% hydro power

of its entire generation capacity [53]. The typical frequency responses in Quebec are illustrated in Fig. 5-12.



(a) Generation Drop-like



(b) Load Shedding-like

Fig. 5-11. Frequency disturbances in Nordic: (a) Generation Drop-like (b) Load Shedding-like

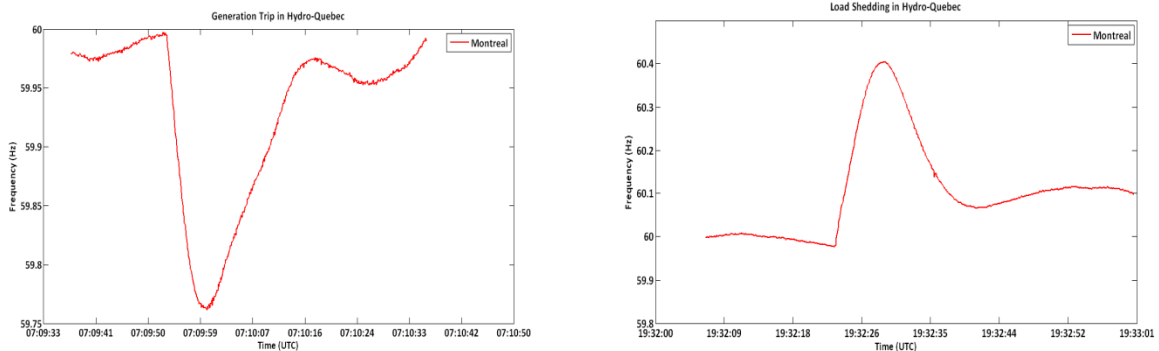


Fig. 5-12. Frequency disturbances in Hydro Quebec: (a) Generation Drop-like (b) Load Shedding-like

5.2.3 Comparison with North America Power Grid

Various metrics regarding system operating and planning can be revealed from these frequency disturbances, e.g. nadir frequency, Quasi-Steady-State Frequency Deviation, frequency response characteristic, etc [54]. All these information would be useful in many aspects, e.g. system operation setting adjustment, guidance of integration of variable renewable energy into systems. Here some preliminary frequency disturbance analysis regarding these metric is performed based on the disturbances collected by the FNET event monitoring system of European power grid.

- **Typical Frequency Excursion**

Fig. 5-13 shows the typical frequency excursions of generation trip in the four North American Interconnections and two European synchronous systems. The frequencies in the different synchronous power system experience quite different recovery procedures following the initial frequency changes, which greatly depend on the generation and load characteristics, the primary and secondary frequency control schemes in different systems.

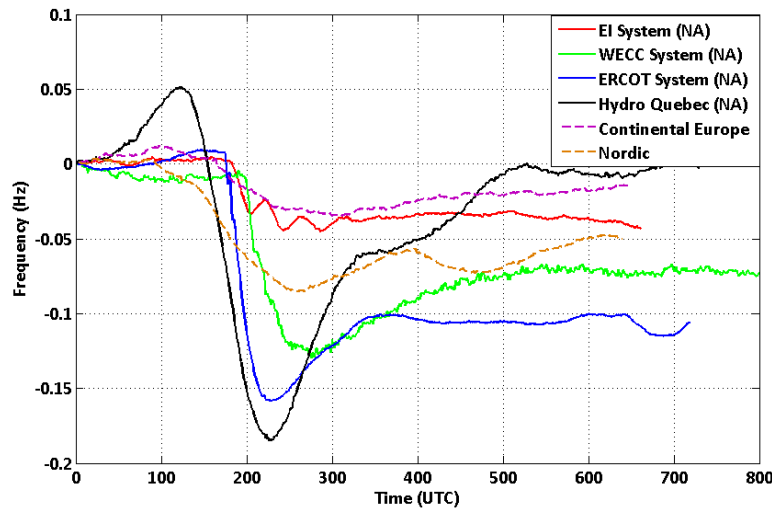


Fig. 5-13. Frequency responses of generation trip in North American and European Power Grid

- **Dynamic Frequency Deviation**

Take one of the frequency response metrics as example, the dynamic frequency deviation, defined in the UCTE operation handbook [54], is treated as the deviation between the pre-disturbance average frequency and the nadir frequency being arrested following the sudden loss of generation.

As shown in Fig. 5-14, for the Nordic power system, the nadir frequency deviation mostly falls in the range of between 60 mHz and 120mHz, while in Continental Europe power system, the frequency deviation mostly falls in the range of between 25mHz and 45mHz, which is similar to the EI system, as shown in Fig. 5-15. Fig. 5-15 also shows the distribution of dynamic frequency deviation of generation trip events in ERCOT and WECC system in 2011. The value is far more less than the maximum dynamic frequency deviation of ± 800 mHz in the UCTE operation handbook [54]. It is reasonable that small power system usually has a large frequency deviation responding to system disturbances. Since with more generation and load involved in frequency control in large power system, the large frequency response characteristics is expected.

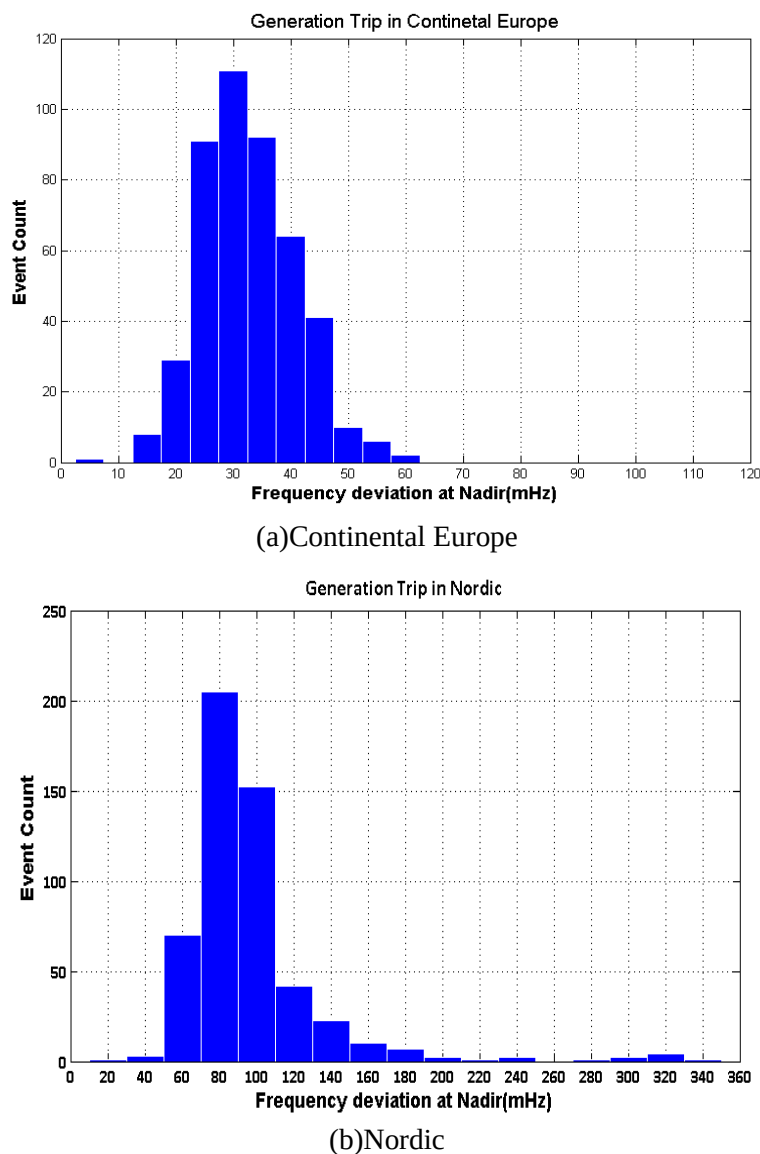


Fig. 5-14. Distribution of frequency deviation of disturbances in (a) Continental Europe and (b) Nordic

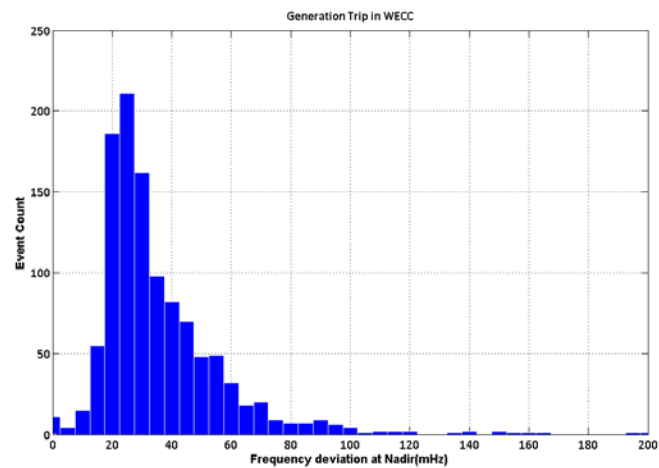
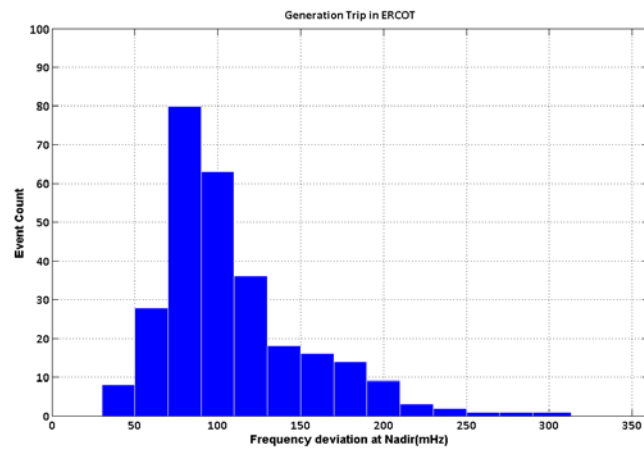
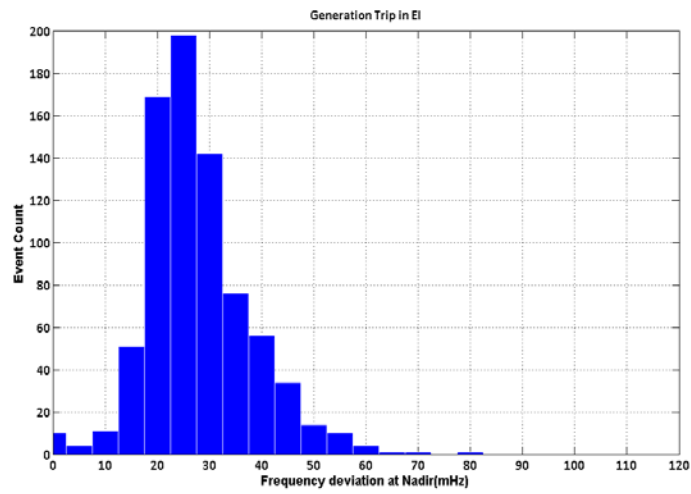


Fig. 5-15. Distribution of Frequency deviation of disturbances in EI/ERCOT/WECC

In the further with the accumulation of the FNET event database of worldwide power grid, a more complete disturbance statistics of the worldwide power grid beyond North America will be examined and compared with North American power grid, as the disturbance statistics the FNET system has provided for North American power grid from 2006 to 2010[6][7].

5.3. Conclusion

The disturbance statistics in the WECC and EI systems is investigated based on the real wide-area measurements taken in the FNET system from 2008 to Sept, 2011. These statistical analysis and comparison shows that a significant increase in the number of load shedding-like disturbances is observed in EI and WECC from 2008 to Sept, 2011, compared with generation drop-like disturbance; the load shedding-like disturbances in both interconnections are most likely to happen in the early morning locally; both the load-shedding-like and generation trip-like events are evenly distributed by day in a week in general.

Besides the North America Power Grid, the FNET system gradually possesses the worldwide event monitoring capability with the recent FDR deployment in the some worldwide countries. Taking the European power grid as example, some frequency disturbances in the European power system captured by the FNET system are illustrated and some preliminary disturbance statistics is also discussed.

With the increasing of FDR deployment in the European power grid, more situational awareness applications can be applied, such as event location estimation. And with further accumulation of the FNET historical event database of other worldwide power grid, e.g. Korean, China, a comprehensive system profile regarding disturbance statistics will be drawn and compared with the North America power grid.

Chapter 6. Analysis of Major Disturbances in North American Power System

6.1. Introduction

Power systems are continuously exposed to various disturbances, e.g. line trip, generation trip, pumped hydroelectric storage unit trip, etc. Local phase angle, frequency and voltage measurement will change simultaneously in response to these disturbances. Therefore, by monitoring these parameters, it would be helpful for us to understand the behavior of a wide-area power system to different types of disturbances and observe the system operation status.

The chapter will investigate several major disturbances in the EI and WECC system recorded by FNET in 2010 and 2011 (Table 6-1), including a HVDC line trip in Hydro-Quebec and New England area, a large generation drop in WECC involving the Pacific HVDC outage, an islanding event in WECC, which caused Alberta separation from other parts of Western power system, a large load drop disturbance causing the blackout in Toronto area, a multi-disturbance event that involves line trips and multi-unit generator trip, and the Southwest Blackout which left millions of San Diego, parts of Arizona and Mexico out of power.

This work is not to identify the cause of these events, however how the disturbances propagated and spread across regions, the system responses to different disturbances. The frequency, voltage and phase angle recordings are examined, and the inter-area oscillatory modes will be analyzed.

Table 6-1 List of Disturbance Events (2010-2011)

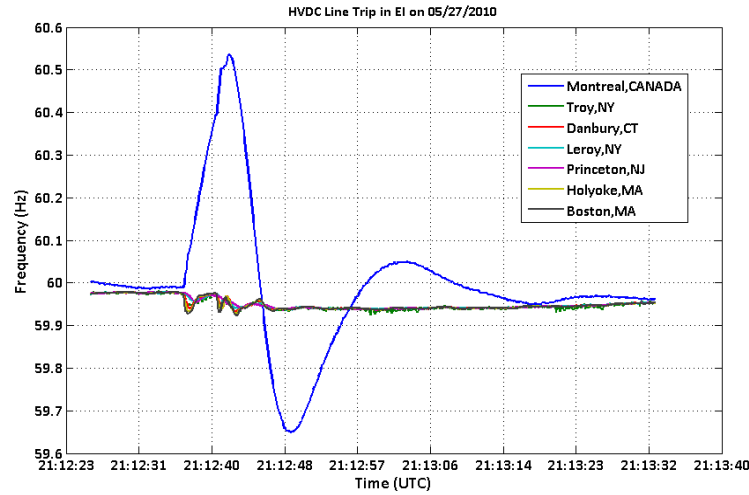
Disturbance Event	Date	Amount (MW)
Loss of HVDC Line in New England	May 27, 2010	~1100
Loss of large load in Toronto area	July 5, 2010	~900
Loss of multi-units and multiple line trips in AL area due to tornado	April 27, 2011	~2000
Loss of large generations in WECC	May 5, 2011	~2000
Islanding of Alberta area	June 1, 2010	N/A
Southwest Blackout in WECC	Sept 5, 2011	N/A

6.2. Event Case Study

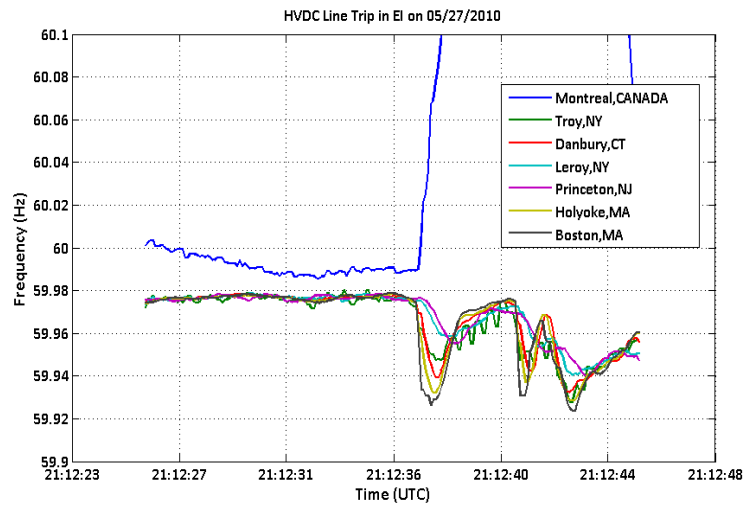
6.2.1 HVDC Line Trip in EI

With FDRs being deployed at the two ends of High-Voltage Direct-Current (HVDC) transmission lines, e.g. FDRs located on Montreal and New England areas for Quebec-New England HVDC facility, FDRs located on Radisson and Winnipeg for Nelson River HVDC facility, there are several HVDC-related disturbances detected by the FNET system in 2010 and 2011. One of them, which happened on May 27, 2010, is discussed in this section. It was caused by the loss of HVDC facility in Littleton MA carrying 1100MW.

The frequency excursion of this HVDC line trip disturbance is shown in Fig. 6-1. Only the FDRs near New England area are listed. This trip lasted about 1 minute before clearing. As shown in Fig. 6-1(a), the frequency excursion of FDRs in the New England area appeared as response to a generation drop disturbance and the Montreal FDR in the Quebec area as response to a load shedding disturbance. This depended on the power flow direction on HVDC line at the time it was tripped. At the time of this disturbance the Hydro Quebec was transferring power into New England area. The FNET situational awareness system reported a generation trip-like event in the EI system at the disturbance time, with an FNET-estimated drop of around 600MW.



(a)



(b)

Fig. 6-1. Frequency excursion (a) during and (b) at the start of HVDC line trip event of 05/27/2010

The relative phase angle during this disturbance is shown in Fig. 6-2. The relative angle value takes the FDR in OH as the reference. Furthermore, the phase angles are normalized to zero at the start to eliminate arbitrary angle offsets caused by phase shift from transmission to distribution networks. All the “angles” mentioned in the following sections are the relative phase angle taking one FDR as the reference and being normalized to start at zero. As shown in Fig. 6-2, the angle of the FDRs in the New England area presented obvious oscillations due to the line trip. Among these FDRs in New England area, the FDR in Boston, MA, which is closest to the HVDC facility, exhibited the earliest and largest swings in both frequency and angle.

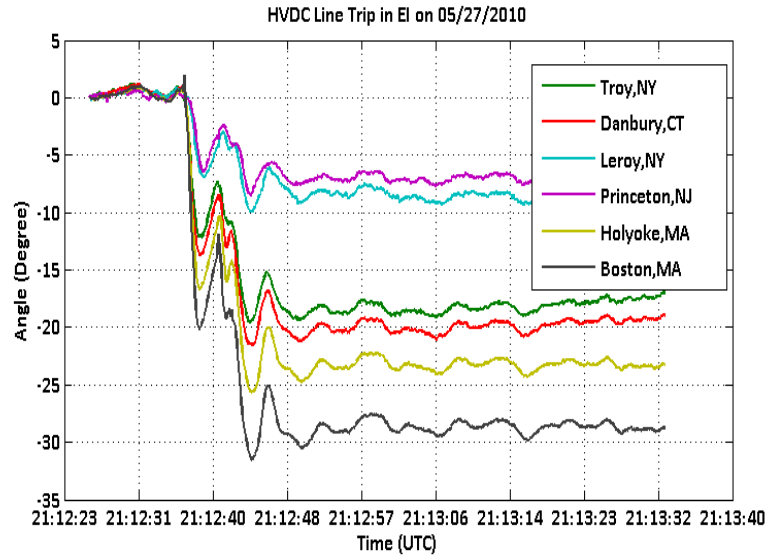


Fig. 6-2. Relative phase angle of FDRs near New England area during the HVDC line trip of 05/27/2010

Taking relative phase angle from all FDRs (not limited to FDRs listed in Fig. 6-2) as modal analysis inputs with Matrix Pencil method [13], a dominate mode near 0.2Hz is observed. The mode shape of 0.2Hz mode is shown in Fig. 6-3. Only those FDRs with relatively large oscillation magnitudes are listed. The colors of the bars indicate different oscillation clusters. The heights of the bars are proportional to the oscillation magnitudes. It is obvious that the New England areas oscillated against the southern areas and northwestern areas of EI at 0.2Hz.

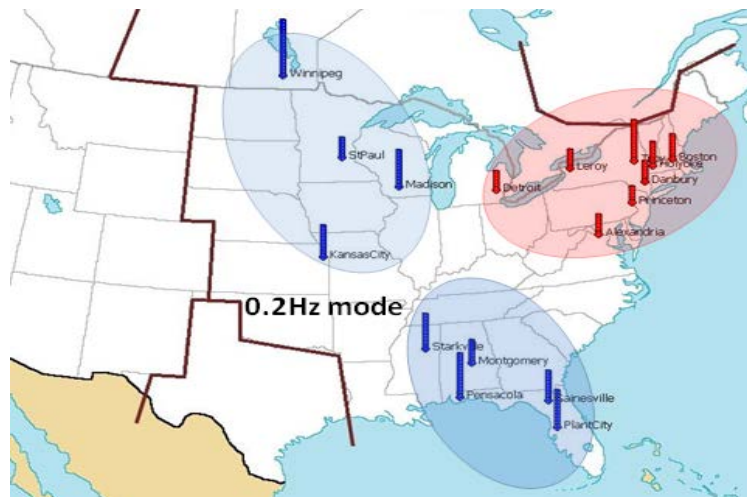


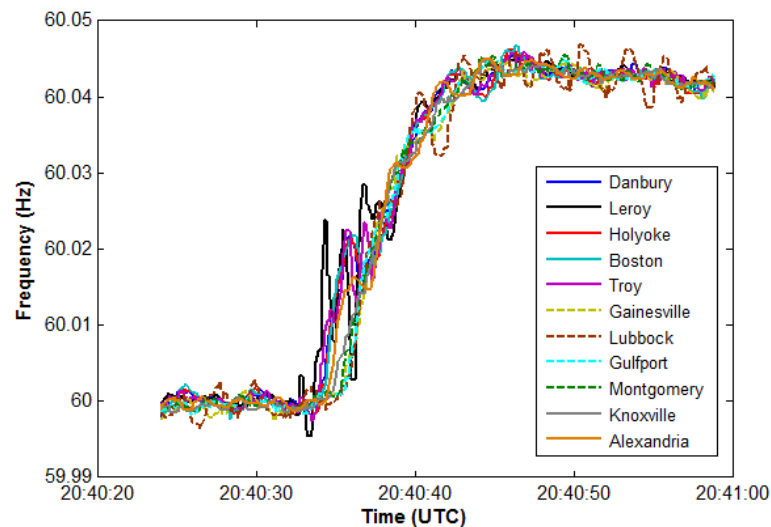
Fig. 6-3. 0.2Hz Mode shape of HVDC line trip disturbance of 05/27/2010

6.2.2 Toronto Blackout

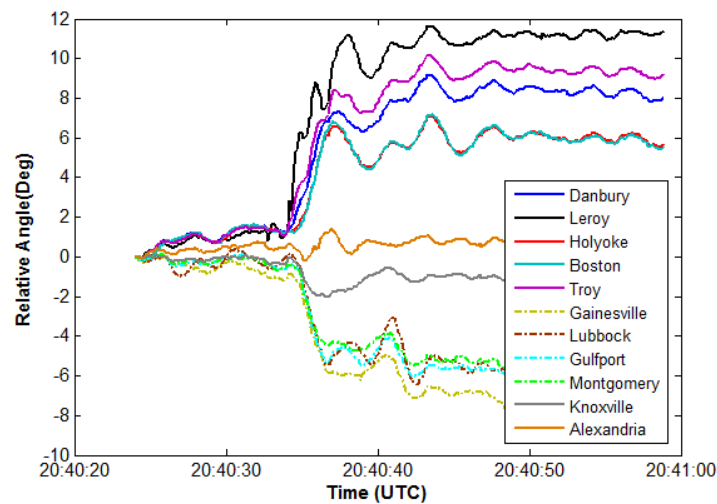
There is a major disturbance captured by FNET online event detection application as load shedding-like disturbance on July 5, 2010. The disturbance caused a blackout near Toronto area. It was later confirmed that this disturbance was caused by a 230 kV breaker fault in the

west Toronto area resulting in 900MW lost off the substation and another 600 shaken off the area as a result of the fault.

The frequency excursion and relative angle oscillation are shown in Fig. 6-4, where only a selection of all FDRs located in the EI system is listed. The selected FDRs cover southern areas, central areas of the EI system, and the areas near the disturbance center.



(a)



(b)

Fig. 6-4. (a). Frequency excursion and (b) Relative phase angle of FDRs during Toronto Blackout of 07/05/2010

As shown in Fig. 6-4(a), the FDR located in Leroy, NY, which is close to the disturbance center, saw an immediate frequency rise right after the disturbance. From the relative angle plot in Fig. 6-4(b), it is obvious that during the oscillation the system was generally grouped into two

major parts: the northern area (Danbury, Leroy, Holyoke, Boston, and Troy) oscillated against the southern area (Gainesville, Lubbock, Gulfport, and Montgomery). The central area of the EI system (Knoxville and Alexandria) did not show obvious oscillations.

The modal analysis result utilizing Matrix Pencil method is shown in Fig. 6-5, with the red star indicating the disturbance center. Two dominant modes are observed, one is near 0.3Hz, the other is near 0.5Hz. In both of the two modes, the northeastern area near the disturbance center, oscillated against the southern area of the EI system. According to the oscillation magnitudes indicated as the height of bars on the map, the northern area presented larger oscillation magnitude than the southern area at 0.5Hz, while the southern area took the lead at 0.3Hz.

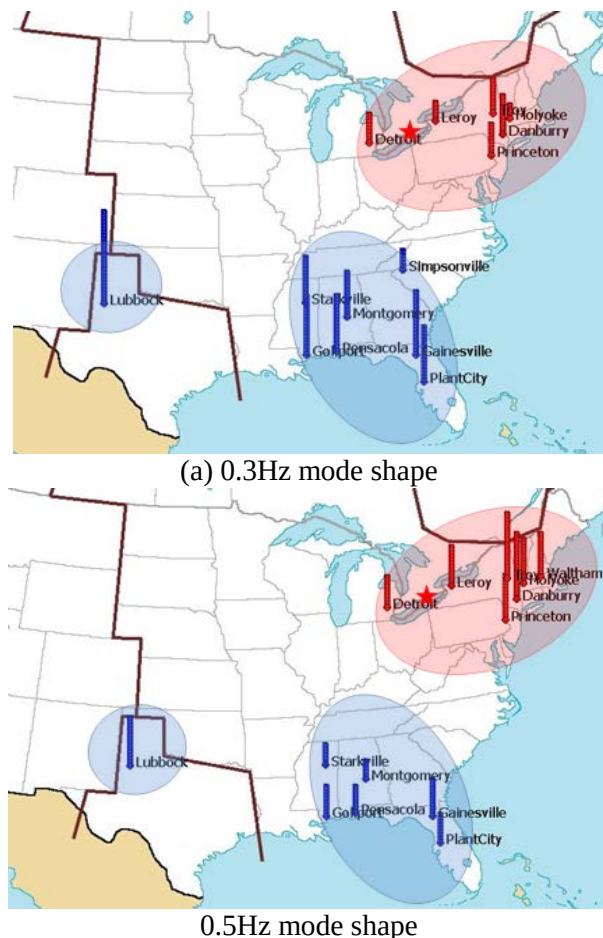


Fig. 6-5.. Mode shape of (a) 0.30Hz and (b) 0.5Hz in Toronto Blackout of 07/05/2010 (the Lubbock unit belongs to the EI system)

6.2.3 Multi-disturbance event in EI

On April 27, 2011, the FNET system captured a large generation drop event in the EI system with estimated generation loss of around 2000MW. It was later confirmed that due to the severe weather conditions in the southeast areas, multiple generation units were tripped in Alabama area and several high-voltage transmission lines were disconnected at that time [51]. The possible time sequence of these disturbances and system dynamics during this event can be observed from FDR measurements as shown in Fig. 6-6 through Fig. 6-9. For the clarity of display, one those FDRs which are close to Alabama area are selected and plotted here.

Fig. 6-6 shows the frequency excursion of the entire multi-disturbance event. During this event, the system frequency dropped to 59.89Hz, and it took about 6 min for the system frequency to be recovered to 60Hz. As shown in Fig. 6-7, before the large frequency decline, several transmission line disturbances possibly occurred between 21:35:08 UTC and 21:35:51 UTC. The FDR unit located in Knoxville, TN (the green line) saw the earliest swings. Following these line trips, multiple generation units tripped at around 21:36:30 UTC as shown in Fig. 6-8, the unit in Knoxville, TN (green line) detected the frequency decline earliest.

When looking into voltage measurements, for the ease of comparison, the voltage measurement of every FDR is normalized by dividing by the average of pre-disturbance measurement over a 10-sec time window. As shown in Fig. 6-9, the voltage suppression and oscillation caused by these disturbances (line trips and generation drop) were clearly observed at the same time. Compared with other units, it is noticeable that the transient dynamics of the line trips and generation drop were only reflected on the distribution-level voltage measurements of the close FDRs to disturbance location, namely the Knoxville unit in TN (the green line) and the Marion unit in IL (the orange line). The observability of system dynamics from the distribution level voltage measurement will be affected by the distance of the measurement points to the event location, and event size.

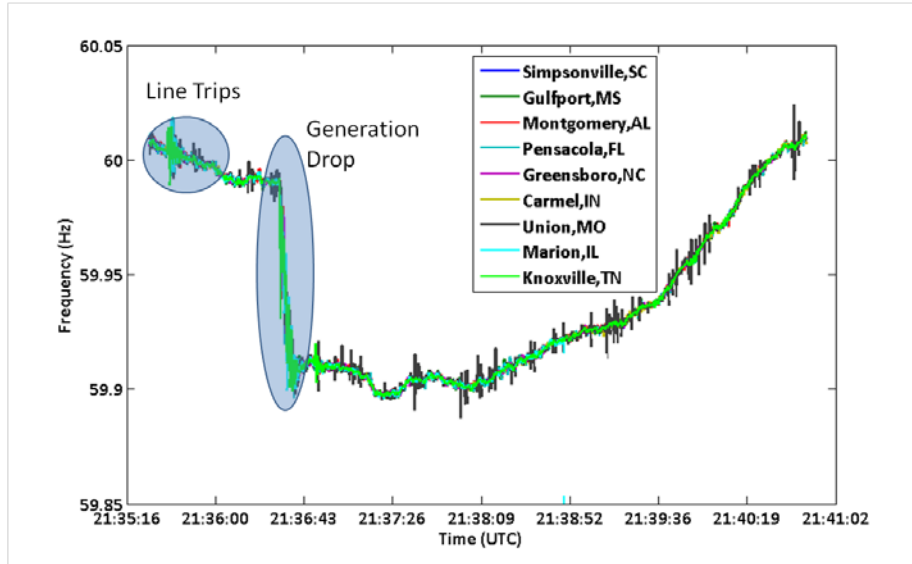


Fig. 6-6. Frequency excursion of generation trip on 04/27/2011

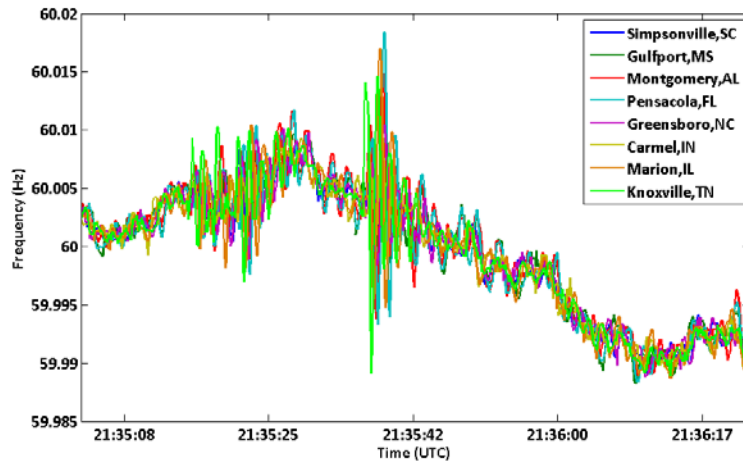


Fig. 6-7. Frequency detail of line trips before generation trip on 04/27/2011

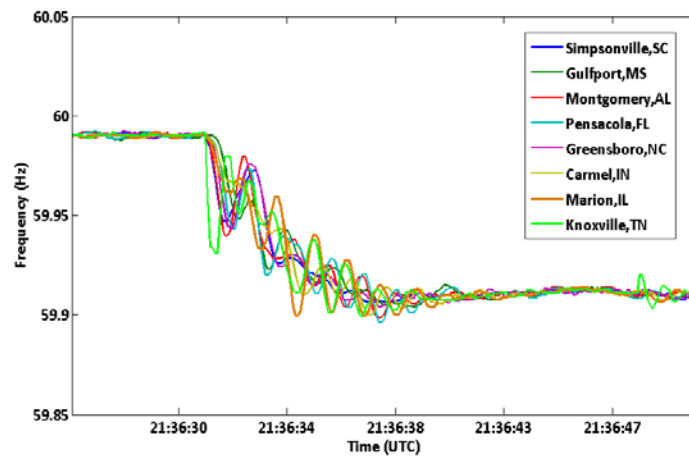


Fig. 6-8. Frequency detail during generation trip on 04/27/2011

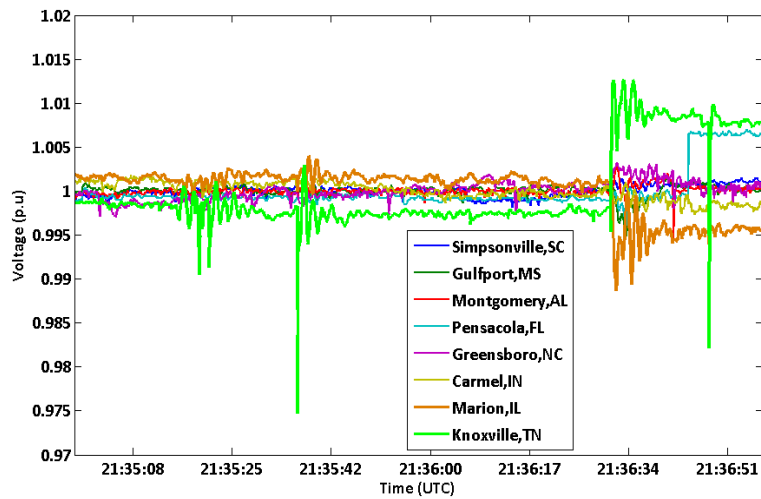


Fig. 6-9. Voltage plot of generation trip on 04/27/2011

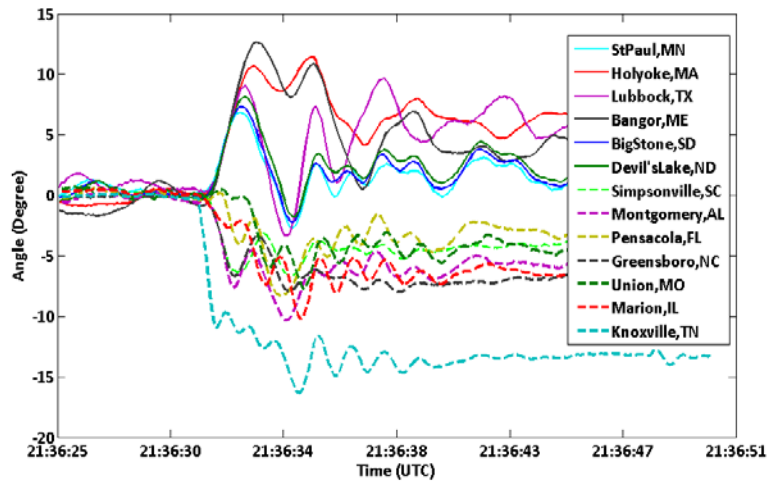


Fig. 6-10. Relative phase angle of generation trip on 04/27/2011 (Taking the Ohio unit as reference)

The relative angle oscillation is shown in Fig. 6-10, where only selected FDRs in the EI system are listed. These FDRs are generally grouped into two major parts based on the angle oscillation, one is the FDRs (dash line) close to the event location (AL), and the other (solid line) is far from event area.

The modal analysis result utilizing Matrix Pencil method is shown in Fig. 6-11, with the red star indicating the event location. One dominant mode near 0.2Hz is observed. For the 0.2Hz inter-area mode, the northeastern area exhibited largest oscillation magnitude, and oscillated against the southern and northwestern areas. This large generation loss in the southern area incited a strong inter-area oscillation even farther in northwestern and northeastern part of the EI power system.

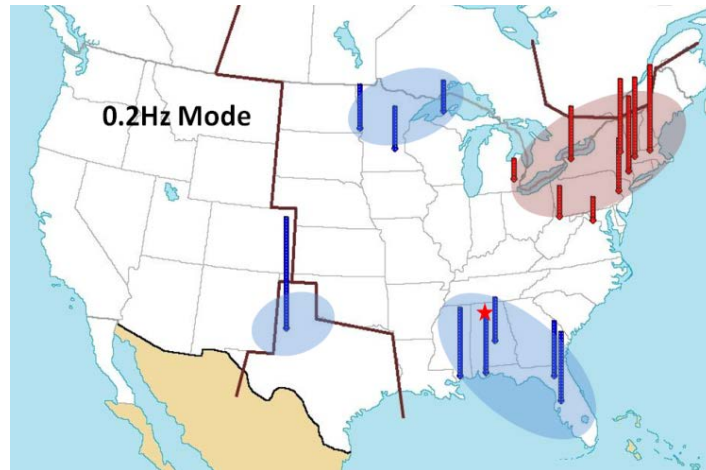


Fig. 6-11. 0.2Hz mode shape of generation trip on 04/27/2011
(The FDR unit located in Texas belongs to EI)

6.2.4 WECC Generation Trip with Pacific DC Intertie Outage

A large generation drop event (>2000MW) was captured by FNET on May 5, 2011 in the WECC system, with an estimated generation drop amount of up to 2026MW. It is confirmed later that this event is caused by an outage of the Pacific DC Intertie which caused approximately 2370MW generation drop. The Pacific DC Intertie (PDCI) is an electric power transmission line that transmits electricity from the Pacific Northwest to the Los Angeles area using HVDC. The system dynamics of this event is shown in Fig. 6-12 through Fig. 6-15.

Right before the large frequency decline in Fig. 6-12, frequency oscillations appeared among all FDRs between 19:38:37UTC and 19:38:43UTC, which might indicate the PDCI outage. The FDRs in WA and CA responded earliest, which are located at the two ends of the PDCI. The FDRs in northern (MT, WA) and Alberta area saw the largest oscillation magnitude, located at the north side of PDCI. Such oscillations were also clearly observed in voltage magnitude measurements at the same time in Fig. 6-14.

Immediately following the possible line outage, the system frequency dropped to as low as 59.71Hz in 6 sec due to the large generation loss in Fig. 6-13. It took about 9 minutes for the system frequency to be recovered to 60Hz. There were significant oscillations associated with the frequency decline in the northern part of the WECC system (MT, WA and Alberta units).

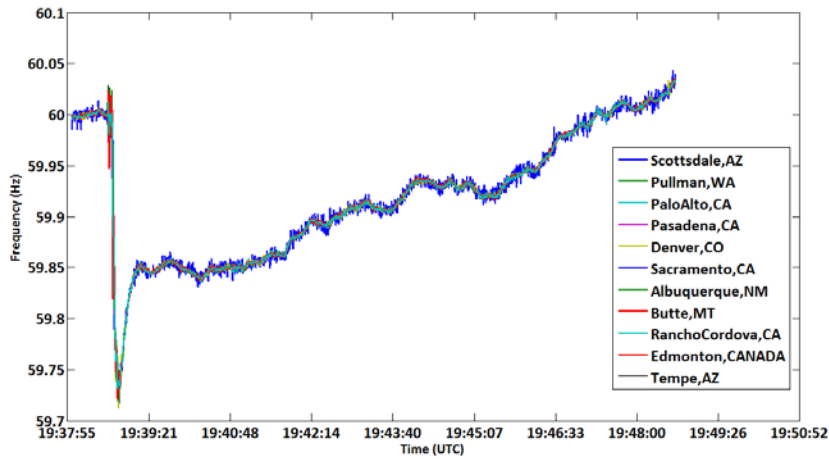


Fig. 6-12. Frequency excursion of WECC Generation Trip of 05/05/2011

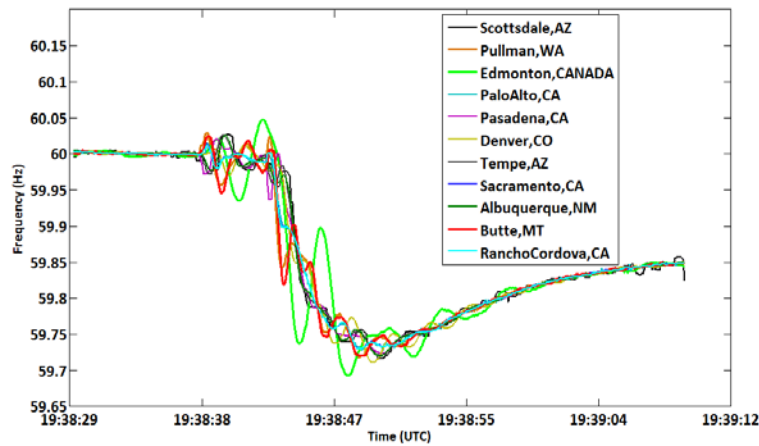


Fig. 6-13. Frequency detail of WECC Generation Trip of 05/05/2011

The relative angle oscillation is shown in Fig. 6-15. The FDR in Alberta saw the largest oscillation magnitude, with maximum pea-to-peak magnitude of 50° . The modal analysis result utilizing Matrix Pencil method is shown in Fig. 6-16. Three major modes are observed in this case, $\sim 0.2\text{Hz}$, $\sim 0.4\text{Hz}$ and $\sim 0.6\text{Hz}$. For the 0.2Hz mode, the southeastern area (AZ, NM) oscillated against the other areas of the WECC system. The Alberta unit exhibited the most significant oscillation strength on this 0.2Hz mode. For the mode near 0.4Hz , the Alberta and the southeastern areas (CO, AZ) oscillated against the central CA and northern areas (MT, WA).

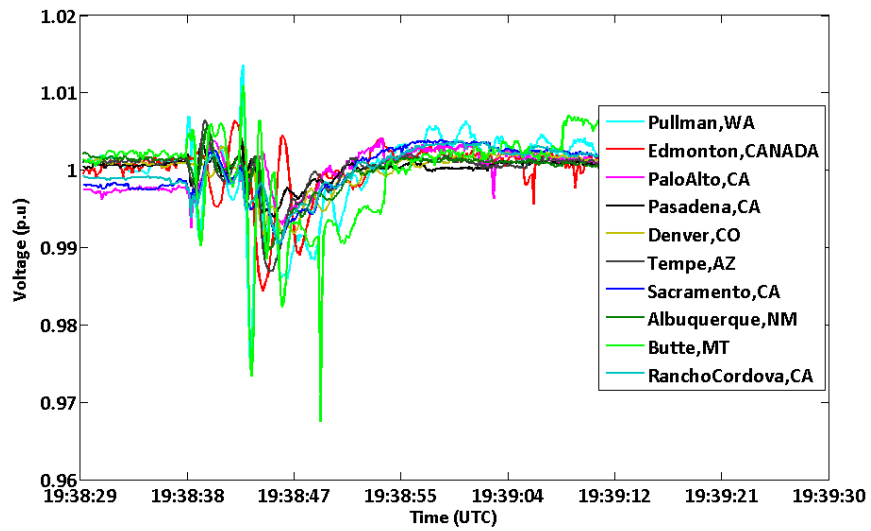


Fig. 6-14. Voltage plot of WECC Generation Trip of 05/05/2011

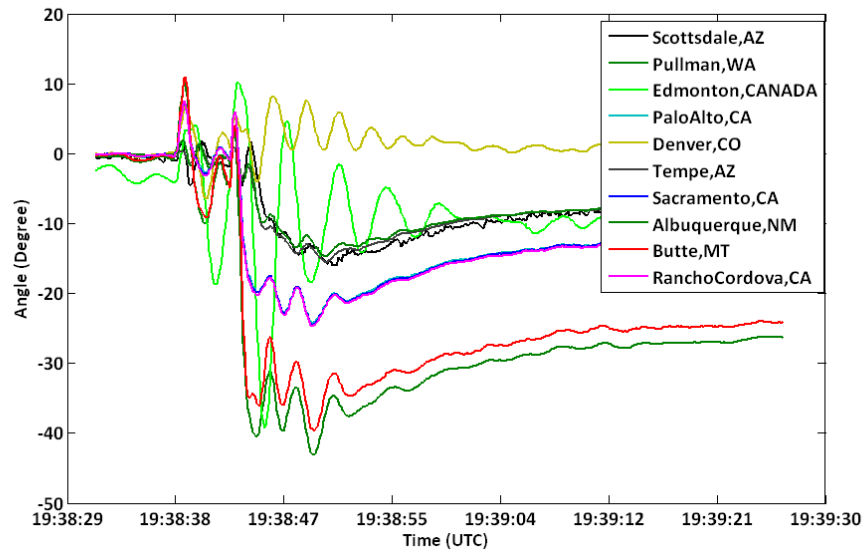


Fig. 6-15. Relative phase angle of WECC Generation Trip of 05/05/2011
(Taking the Pasadena unit as reference)

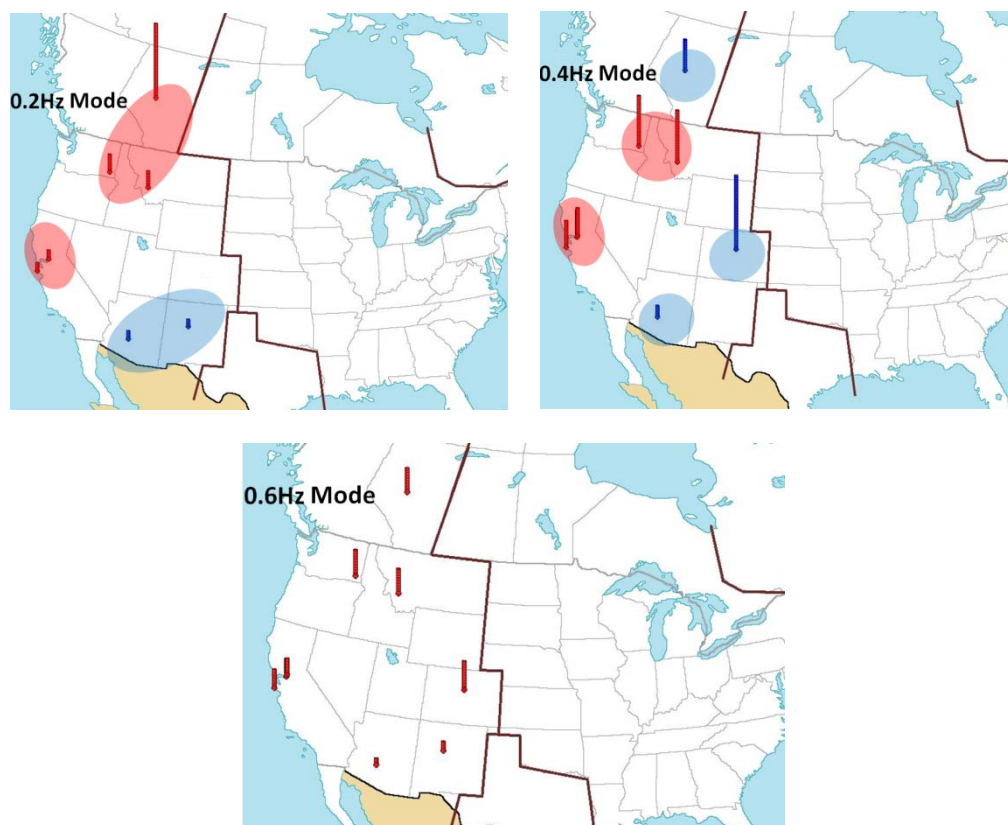


Fig. 6-16. Mode shape of WECC generation trip of 05/05/2011

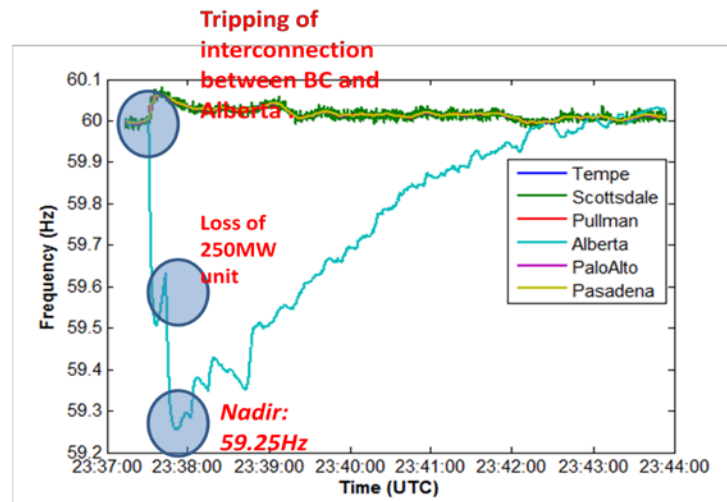
6.2.5 Alberta Islanding in WECC

Another significant event captured by FNET in 2010 is an islanding event in the WECC system on June 1, 2010, in which the Alberta area was disconnected with WECC system. The separation of Alberta was caused by the tripping of the 500kv-tie with British Columbia. Following the line loss there is subsequent generator trip (250 MW) coupled with the loss of import from BC.

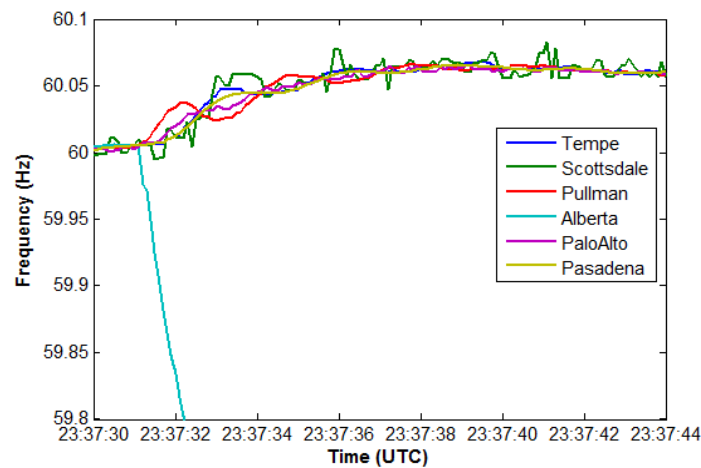
As shown in Fig. 6-17, the separation began at around 23:37:31 UTC, when the single interconnection between British Columbia and Alberta system. The separation lasted about 5 minutes before the island and the other parts of the WECC system were reconnected. Immediately after islanding, system frequency was split into two groups. The Alberta unit saw a steep frequency drop of around 0.5Hz. And the other areas saw a frequency rise of 55 mHz in 4 sec, which was possibly due to generation excess in this area caused by Alberta area disconnection. At around 23:37:40 the event was exacerbated by the inadvertent loss of a 250

MW unit while the system was islanded subsequently. The frequency excursion in Alberta went to approximate 59.25Hz.

The out of synchronism of interconnected system was also observed by the dramatic angle separation between the Alberta area and the other WECC areas as indicated in Fig. 6-18. And the FDR located in Pullman, WA, which is in the close proximity to the separation area, had the earliest response and largest oscillation magnitude than other FDRs in both angle and frequency.

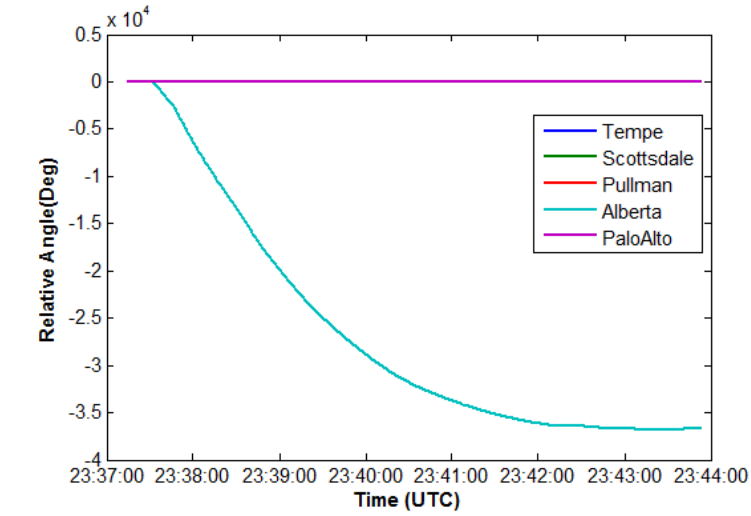


(a)

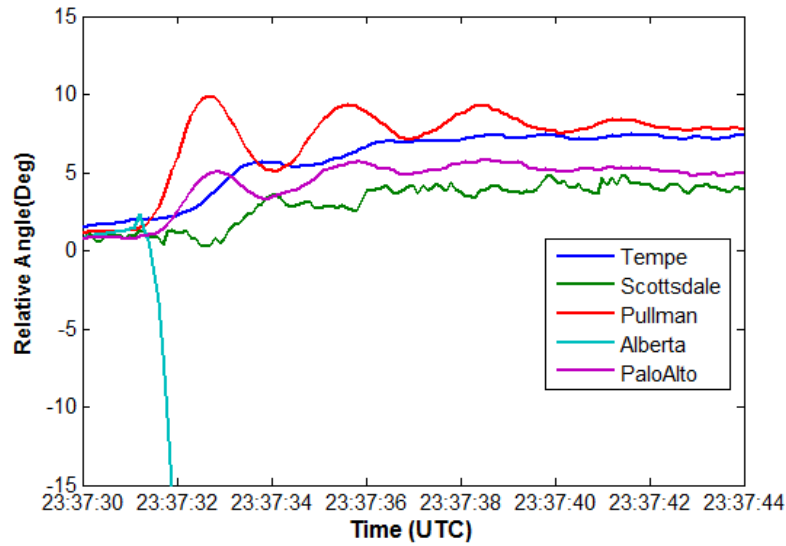


(b)

Fig. 6-17. Frequency excursion (a) during and (b) at the start of WECC Islanding event of 06/01/2010



(a)



(b)

Fig. 6-18. Relative phase angle (a) during and (b) at the start of WECC Islanding event of 06/01/2010

Taking all FDR data except Alberta unit as modal analysis inputs with Matrix Pencil method, one dominate mode near 0.33Hz is observed. The oscillation clustering pattern on this mode is shown on a map in Fig. 6-19. It turns out that the northwestern areas (WA area) and central CA areas oscillated against southeastern areas (AZ area) at 0.33Hz. The Pullman unit in WA exhibited the most significant oscillation magnitude.

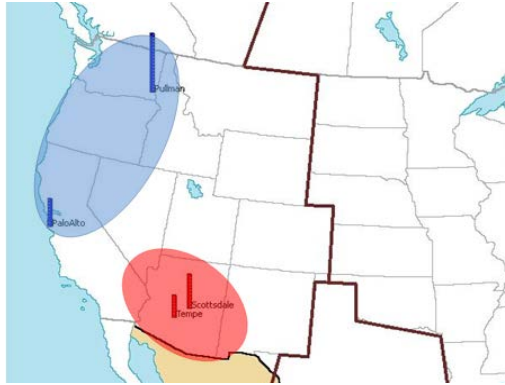


Fig. 6-19. Mode shape of 0.33Hz in WECC Islanding 06/01/2010

6.2.6 Southwest Blackout in WECC

On Sept 5, 2011, a chain of events occurred in WECC, which resulted in massive blackout in southwest parts of Western Interconnection [52]. The blackout was incited initially by a 500-kV transmission line trip, and then a sequence of system breakdowns finally resulted in this large blackout, which left millions of San Diego, parts of Arizona and Mexico out of power.

The possible time sequence of these disturbances and system dynamics during this blackout can be observed from FDR measurements as shown in Fig. 6-20 through Fig. 6-26. Fig. 6-20 shows the frequency trend covering the entire southwest blackout. From the frequency trend, the following significant disturbances can be observed [52]:

1. 500-kv transmission line trip at 22:37UTC
2. Another system breakdown at 22:38 UTC
3. San Diego islanding
4. Nuclear plant trip

At 22:37 UTC, a 500-Kv transmission line tripped when the series capacitor was taken offline at the substation (Fig. 6-21a). The transmission line runs from Yuma, AZ to San Diego area, it s one the two lines that carry power to San Diego. The other runs down from north. The system seemed to work properly after the trip by redistributing the power flow for about 10 minutes. The Zoom-in plot in (Fig. 6-21b) shows the electromechanical wave propagation, in which the units in AZ, NM responded to this line trip earliest.

From around 22:38 UTC, outages cascaded across southwest, causing interruptions for utilities in South California (Fig. 6-22). As shown in Fig. 6-22, there was a sudden frequency drop, and then followed by a rapid frequency rise when the San Diego area was islanding from the other area in WECC. Right after the islanding, the San Onofre nuclear plant tripped, and the

key power transmission from North to San Diego was turned off. Finally the outage spread across the entire San Diego. The generator drop brought the frequency out of San Diego areas decline. During these disturbances, the FDRs in South CA, CO, NM and AZ saw large frequency oscillations.

When looking into voltage measurements, the normalized voltage measurement of the above time ranges are shown in Fig. 6-23 and Fig. 6-24, the voltage suppression and oscillation caused by these disturbances were clearly observed at the same time. Especially the FDR unit located in south California (green line) saw the largest oscillation. The relative angle oscillation is shown in Fig. 6-25 and Fig. 6-26. The FDR in Tempe, AZ is chosen as the reference unit.

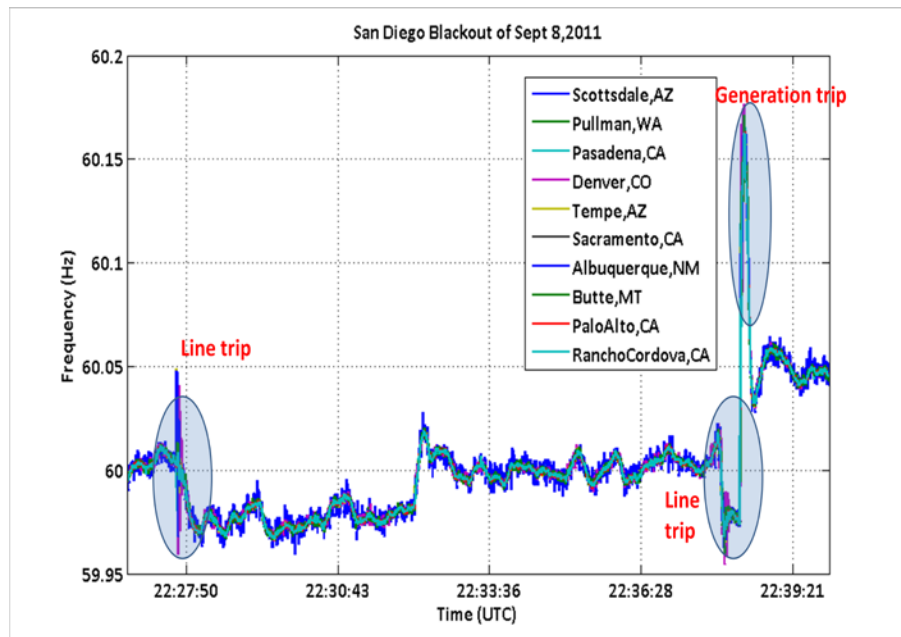
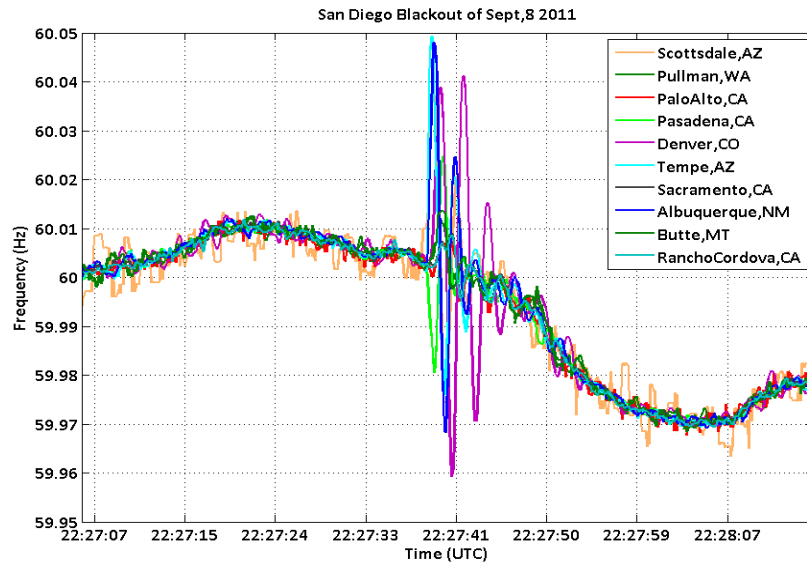
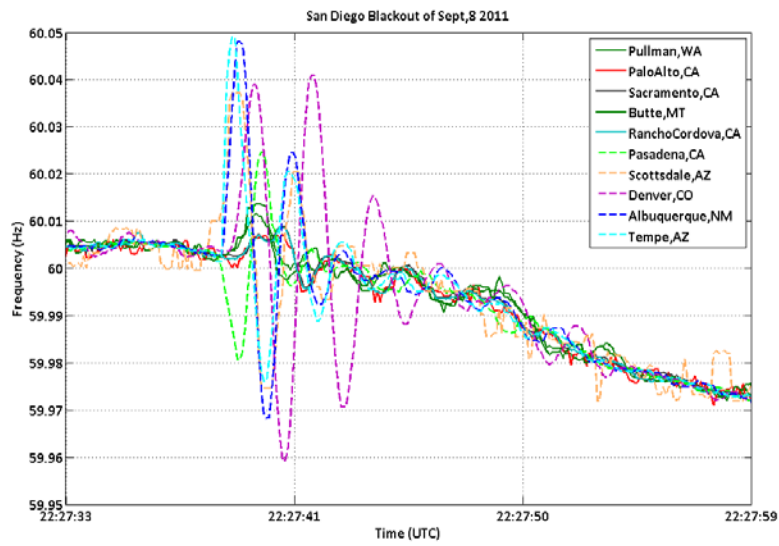


Fig. 6-20. Frequency excursion of Southwest Blackout of 09/08/2011



(a)



(b)Zoom in

Fig. 6-21. Frequency excursion of Southwest Blackout of 09/08/2011 – 500kv-line trip

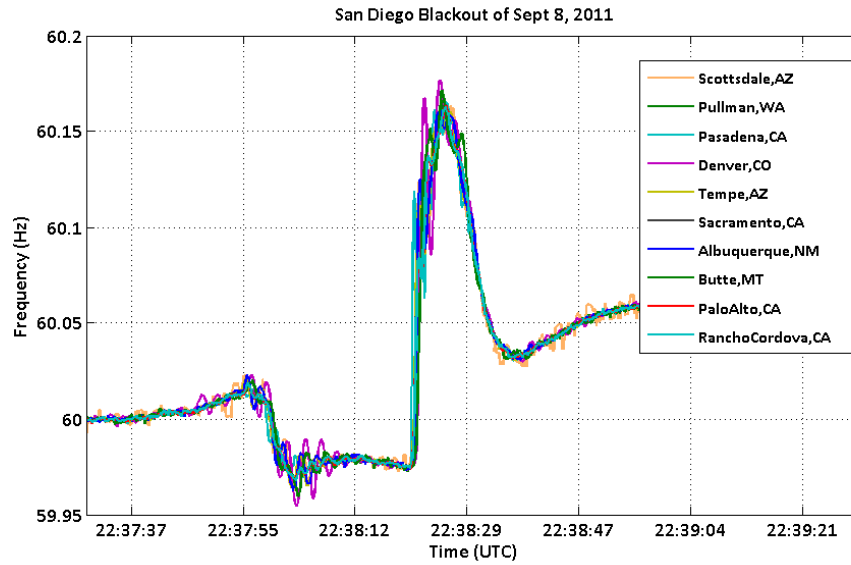


Fig. 6-22. Frequency excursion of Southwest Blackout of 09/08/2011 – San Diego Blackout

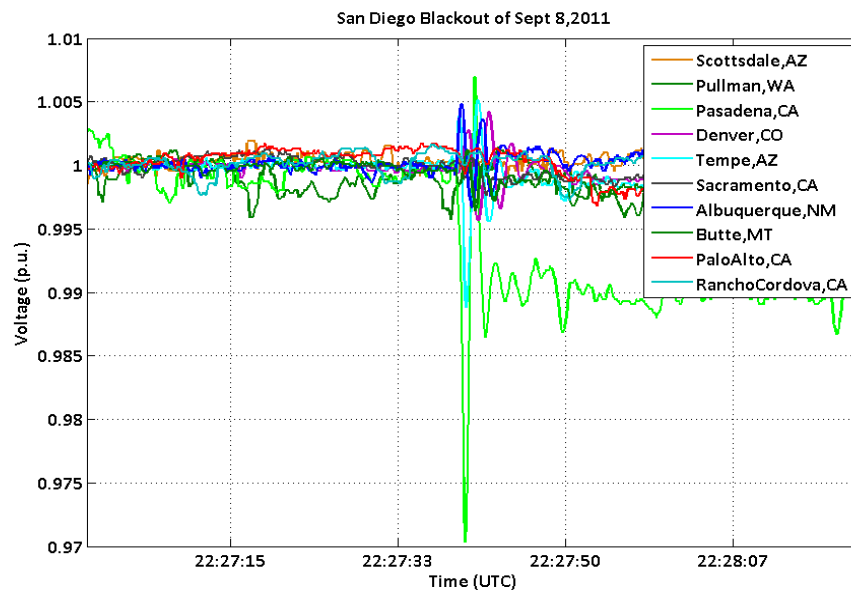


Fig. 6-23. Voltage plot of Southwest Blackout of 09/08/2011 – 500kv-line trip

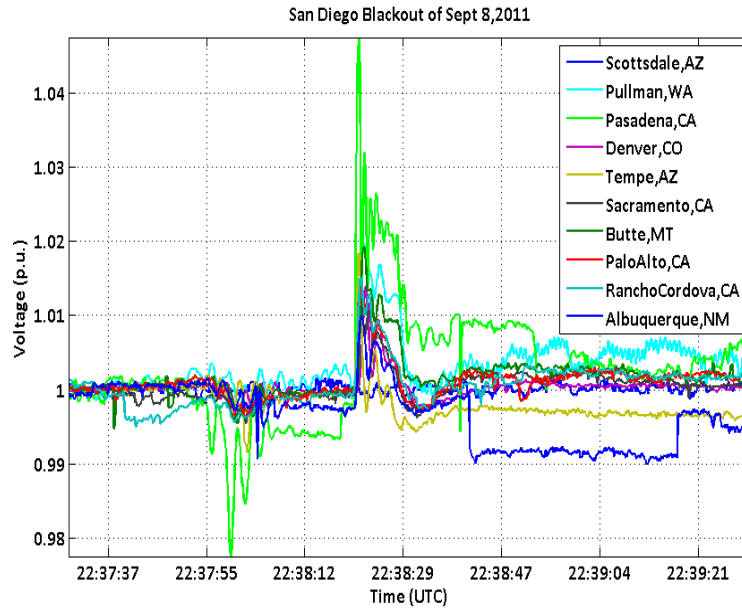


Fig. 6-24. Voltage plot of Southwest Blackout of 09/08/2011 –San Diego Blackout

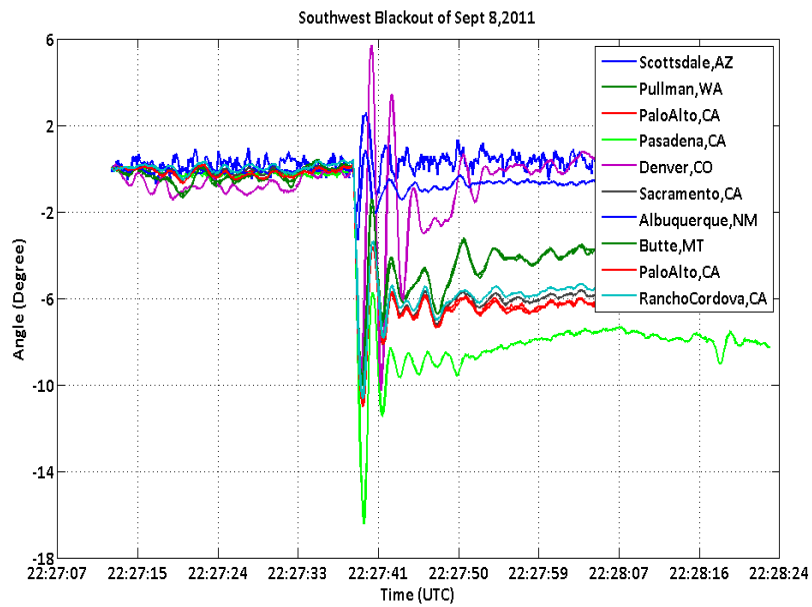


Fig. 6-25. Relative angle plot of Southwest Blackout of 09/08/2011 – 500kv line trip

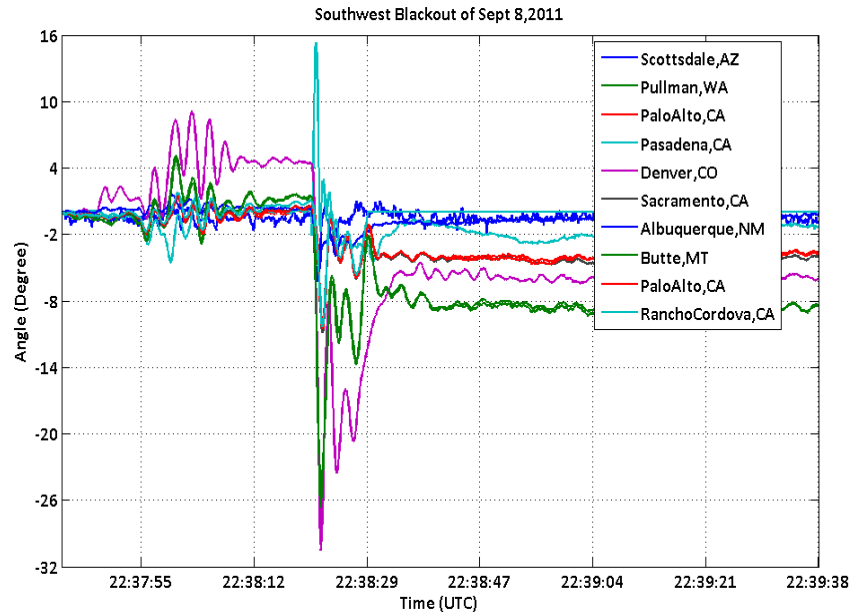


Fig. 6-26. Relative angle plot of Southwest Blackout of 09/08/2011 – San Diego Blackout

6.3. Conclusion

A collection of large disturbances in the EI and WECC systems from 2010 to 2011 are analyzed in this chapter, including a HVDC line trip, the Alberta islanding, one large load drop disturbance in Toronto area, two significant generation drop with line trips involved in WECC and EI respectively and the large Southwest Blackout in WECC. Analysis of frequency, voltage magnitude, and phase angle from FDR recordings are performed. The oscillation mode shapes are analyzed when there are obvious oscillation associated, utilizing the relative voltage phase measurement. The valuable power system dynamics information obtained from these distribution-level phase measurement devices proves the feasibility and effectiveness of monitoring power system at a low voltage level.

Chapter 7. Modal Analysis of FNET Angle Oscillation in Western Interconnection

7.1. Introduction

Inter-area oscillations in large power systems can severely disrupt system operations and induce further disturbances. In most cases power system oscillations are directly associated with power system events, e.g. the tripping of generator, load shedding, line tripping or some other system operations, or they can be ambient. Poorly-damped low-frequency inter-area oscillations can occur frequently, especially in areas where there is a weak interconnection. Therefore, the monitoring of the inter-area oscillation behavior is important for operating and planning of a large interconnected power system. Due to wider-area monitoring ability and the high accuracy of measurement data that the FNET system possesses, power system oscillations can be monitored from both FNET phase angle recordings[21][22] and FNET frequency recordings[24].

Since late 2009, an angle-based oscillation detection module has been developed and implemented on the FNET server, which has captured a lot of low frequency inter-area oscillations in EI and WECC systems. The angle oscillations in EI have been well analyzed based on FNET wide-area measurements [21][22][24]. As a successor of previous works, this chapter deals with the low frequency oscillation modal analysis in Western Interconnection.

The Western Interconnection is characterized by frequent dynamic power system oscillations among generator groups due to the loose interconnections and long transmission paths [27]. These oscillations eventually contributed to the August 10, 1996 western blackout. Various technologies and applications have been developed to examine and assess this activity, e.g. the Wide-Area Measurement Systems (WAMS) in the WECC power grid [27]-[32]. The FNET system has accumulated years of dynamic information based on voltage, angle, and frequency in the WECC system. In this chapter, an effort will be taken to examine the oscillatory dynamic behavior in WECC system during various disturbance events recorded by FNET system from 2010 to 2011. The disturbances involve the generation trips and line trips. The Matrix Pencil method is chosen as oscillation modal analysis tool. The common oscillation inter-area modes in WECC will be drawn from the analysis.

7.2. FNET Angle-based Oscillation Modal Analysis

Wang et. al. investigated inter-area oscillation characteristics using FNET frequency measurement data in [21][22]. Due to its low signal-to-noise ratio (SNR), significant filtering must be applied to the frequency data before it can be used as an oscillation detection parameter. This makes the frequency data less suitable for real-time oscillation detection. Since the FNET phase angle is the integral of the frequency deviation from nominal frequency (60Hz), an oscillation of small magnitude in frequency measurement can cause the angle to have larger oscillations [11]. Therefore, when it comes to oscillation detection mechanism design, phase angle data measurements are desired [11].

7.2.1 Data Selection

The phase angle utilized for modal analysis is relative angle deviation instead of absolute phasor angle the FDRs measure at the 120V outlet. The relative angle deviations are obtained by normalizing and referencing absolute phasor measurements.

1) At the first step, take one FDR as the reference unit, each FDR's angle measurements are subtracted from the reference FDR's angle measurements at the same time point.

2) At the second step, each FDR's angle measurement vector is normalized to start from zero degree by subtracting its first angle value, which will eliminate arbitrary angle shifts caused by the angle shifts from transmission to distribution networks.

Fig. 7-1 shows the relative angle plot for a generation trip disturbance in WECC system captured by FNET in 2010. The FDR located in Pasadena, CA is taken as the reference unit. The data section shown between the two dash vertical lines in Fig. 7-1 will be selected as the input data for the modal analysis. For each oscillation disturbance analyzed in Section 7.3, the FDR unit located in Pasadena, CA is taken as the reference unit if it is available. Since the choice of data time window for analysis will affect the modal estimation, especially for the damping ratio, the related parameter setting will be discussed in the next section.

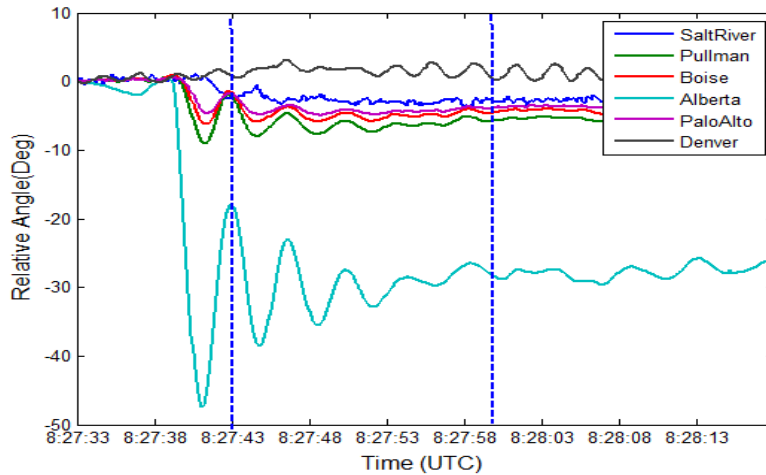


Fig. 7-1. Relative angle plot for a generation trip disturbance in WECC

7.2.2 Matrix Pencil Tools with Parameter Tuning

To date, several mathematical methods from signal processing theory have been used in oscillation modal analysis, such as Prony's Method [33], the Matrix Pencil method [34][35], and Hankel Total Least Square (HTLS) method [36]. These methods all attempt to fit the proper parameters for a sum of exponentially damped sinusoids.

The Matrix Pencil method is a one-step process. It provides computational efficiency and has good statistical properties for signal root estimation. In particular, the Matrix Pencil method uses the Singular Value Decomposition (SVD) to provide an effective way to filter noise. A comparative analysis in [37] has concluded that the Matrix Pencil has good accuracy on mode estimation. In this chapter, the Matrix Pencil method is applied on FNET phasor measurements for oscillation modal analysis.

In order to obtain an accurate estimation of oscillation mode shapes, some parameters of the Matrix Pencil tool need to be adjusted to accommodate different angle oscillation characteristic. Basically the customization of these parameters is through the comparison of the consistency of the modal analysis results with different set of parameter setting.

One of the critical parameters involved in the oscillation modal analysis is the data starting time. Different data section may result in different analysis results. There are two basic rules to be noticed during the data selection. One is the nonlinearity in the first few swings of the oscillation, which can result in an underestimate (or overestimate) of damping ratio for the inter-area modes [37]. And, the other factor that may cause inaccurate estimation of the mode estimation is that as the oscillation decays, the Signal to Noise Ratio (SNR) decreases, that is

how large the ringdown is compared to ambient noise, and the analysis data may enter a very fuzzy zone that may exceed the noise tolerance of the modal analysis tools. Then the data with low SNR is prone to make the analysis tool generate incorrect results.

So according to the above two rules, basically, the modal analysis data starting time should avoid the incipient nonlinear stage of an oscillation, usually after the first one or two swings [37], and keep the oscillation data time window away from of the late stage as the oscillation decays. An example about how to select the data starting time through the comparison of the consistency of the modal analysis results is shown in the following part.

An angle oscillation instance is shown in Fig. 7-2 . Not all the FDR units exhibit strong oscillations with clear exponentially decaying sinusoidal curve. The signatures of Butte and Alberta units are outlined with a decaying sinusoidal curve that is expressive of the modal information of the oscillation. Therefore, only the data of the two units are analyzed in the following process for determining proper data setting.

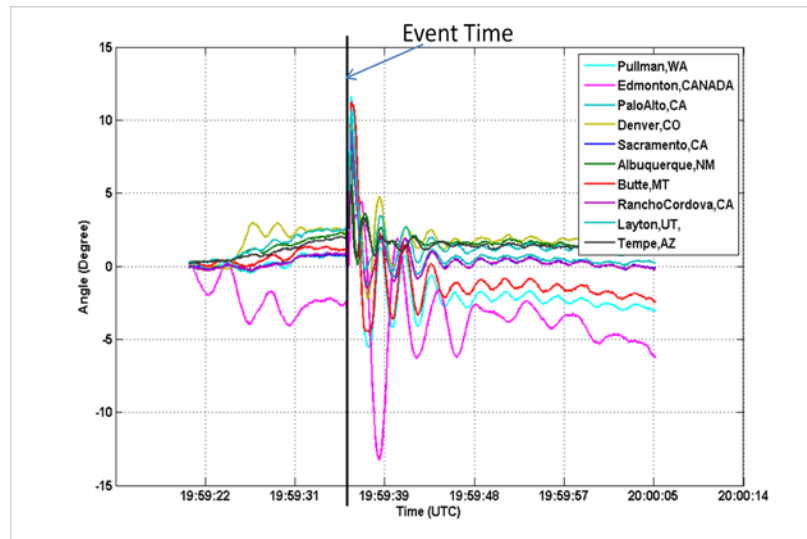


Fig. 7-2. Angle Oscillation in WECC on 05/20/2011

Here the Matrix Pencil modal analyses using 10 second sliding window with the data starting time from the disturbance time point to 5 sec afterwards are performed (51 times of modal analysis). The sliding window moves at the pace of 0.1 sec (one data point) per increment. Fig. 7-3 shows the dominant mode frequency of these two selected units.

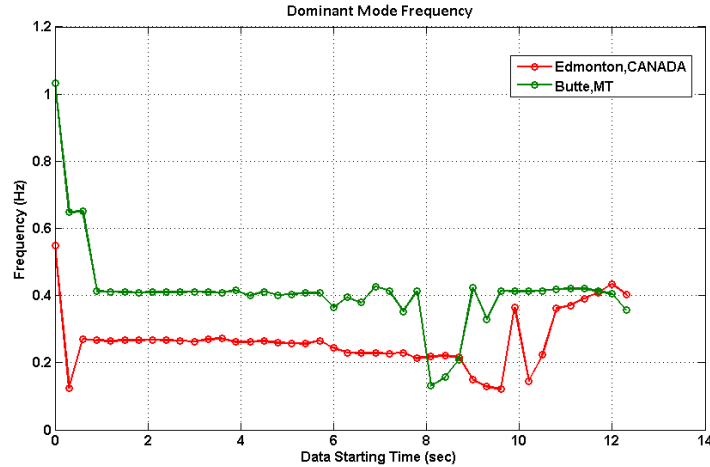


Fig. 7-3. Dominant frequency mode with sliding time window

An optimal data starting time is expected to be obtained from the modal analysis with sliding time window. The group of points on the curve that demonstrate the best consistency should be identified as the optimal data starting point. As shown in Fig. 7-3, the starting time of 2-4 sec after the disturbance point can be a suitable choice for modal analysis. After the start time of 6 sec afterwards, the analysis of Butte unit begins to be irregular and hard to be identified with any consistent patterns, since after 6 sec the oscillation decays for these two units, where the signal-to-noise ratio decreases. And the data time window right after the event time is also hard to be identified with any consistent pattern since the nonlinearity of system right after event time.

When it comes to the damping ratio of dominant mode shown in Fig. 7-4, the same phenomenon can be observed that after 6 sec the analysis results turn out to be irregular and inconsistent, which substantiates the fact that the angle data enter a fuzzy zone when the oscillation decays and the content of the noise exceeds the tolerance limit of the Matrix Pencil algorithm. However, the curves of damping ratio estimation exhibit more fluctuations compared with dominant frequency mode (Fig. 7-3), which is a common problem for all modal analysis techniques [39].

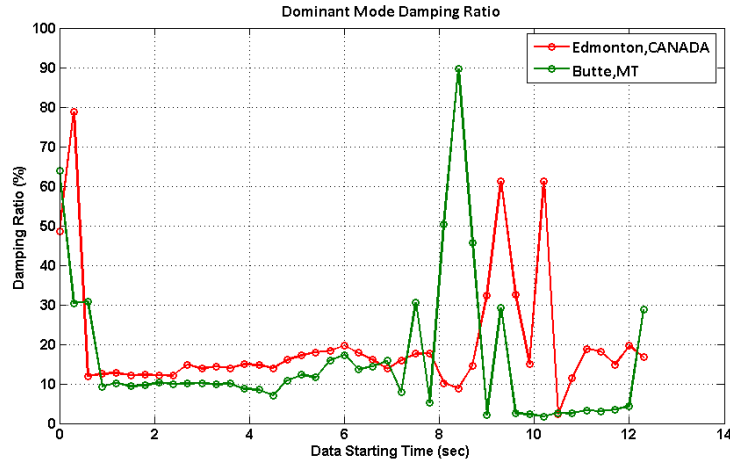


Fig. 7-4. The damping ratio of the dominant mode with sliding time window

In the following case study in Section 7.3, the choice of data starting time will be determined case by case through the moving window crosscheck.

7.3. Modal Analysis of Angle Oscillation in Western Interconnection

7.3.1 Case Selection

There are various ways to perform oscillation analysis in power systems (e.g., oscillations that develop under ambient conditions [38][39], or probing tests [27][40], or under transient conditions). Here the oscillation analysis is performed with oscillation cases that are associated with power system disturbances (e.g., load shedding, generation trip, line trip, etc.). The transient oscillation will be large and violent at the onset, and it carries the highest level of information density. It is valuable to identify the mode information within the ringdown oscillation data.

These oscillations can be incited by different types of disturbances, only two types are considered in this chapter: generation trip and line trip. Table 7-1 lists the selected generation trips to be investigated in the following sections. And Fig. 7-5 shows the geographical location of these tripped plants. The generation trip cases span from large size generation trips (>1000MW) to medium-size ones (500-600MW) with known event location. The line trip disturbances include two basic types: Type-I line tripping with Alberta area connected, Type-II line tripping with Alberta area separated. Relative angle oscillations, frequency excursions, and corresponding modal analysis results will be examined for each case and summarized. The modal analysis is processed with Matrix Pencil method and the parameters are adjusted to

achieve accurate estimation. The inter-area modes of interest are selected by frequency between 0.1 Hz and 1 Hz.

Table 7-1 Generation trip events for oscillation modal analysis in WECC

Time	Plant name	Estimated Amount (MW)
2010-06-18	Palo Verde unit trip	1100
2010-11-04	Jim Bridger unit trip	940
2011-01-06	AESO unit trip	450
2011-03-26	Diablo Canyon unit trip	680
2011-04-28	Mesquite unit trip	840
2011-08-10	Colstrip unit trip	1400
2010-08-29	Colstrip unit trip	760



Fig. 7-5. Distribution of generation trip cases in WECC for oscillation analysis

The map in Fig. 7-6 indicates the name and the location of FDRs in WECC. The FDR in Alberta is critical to track the dynamic performance of the overall system. Since the data from some FDR units will occasionally become unavailable due to a variety of problems, such as network connection issues, loss of GPS, only the FDRs with continuous data streams during the disturbance will be considered as a valid input data channel for the Matrix Pencil tool. Hence, the valid number of FDRs used in modal analysis varies from case to case.



Fig. 7-6. FDR deployment in WECC (as of Sept, 2011)

Since not all the FDRs units exhibit obvious oscillations, and even for one single FDR's measurement, not all the modes are presented with significant oscillation magnitudes, only selected mode information will be output. The criterion used for the oscillation mode output is to set an absolute threshold to filter out those modes with relatively small oscillation magnitudes. And one more thing to be noticed is that the unit in Scottsdale, AZ will be excluded from the mode analysis due to its noisy measurement.

7.3.2 Generation Trip

7.3.2.1 Case 1: Palo Verde Generation Trip on June 18, 2010

There was a trip of Palo Verde unit in AZ on June 18, 2010, with an estimated amount of 650MW. Fig. 7-7 shows the frequency excursion and relative angle oscillation during the disturbance. For this disturbance, only six units were functioning at that time.

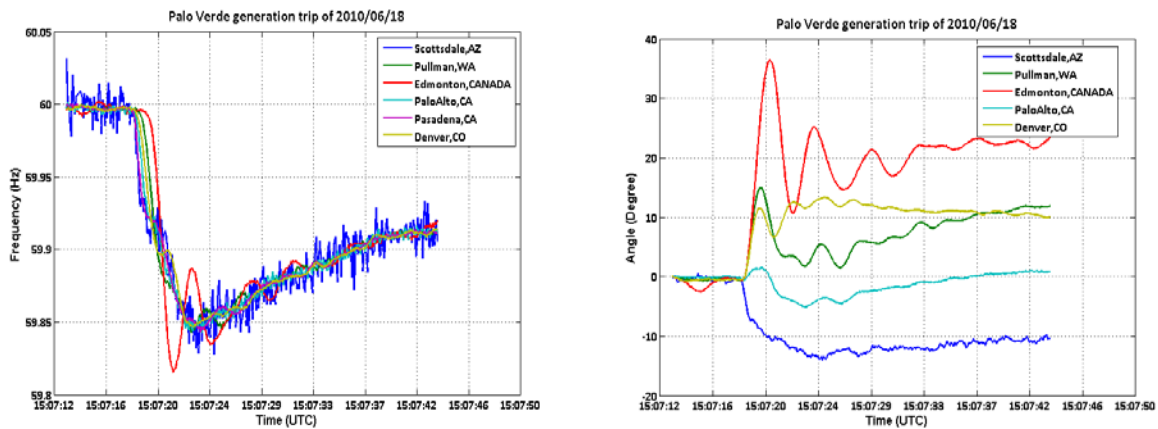


Fig. 7-7. Frequency excursion and Relative angle oscillation of Palo Verde trip of 2010/06/18

The modal analysis results from the Matrix Pencil method is listed in Table 7-2. The 0.2Hz and 0.4Hz modes appear in all the three units. The oscillation clustering pattern of these two major modes is shown in Fig. 7-8 .

Table 7-2 Modal analysis results of Palo Verde generation trip of 2010/06/18

Modes (Hz)		Pullman	Alberta	Palo Alto	Tempe
0.2	f	0.249	<u>0.249</u>	<u>0.236</u>	<u>0.290</u>
	α	3.44	13.49	20.45	43.08
0.4	f	<u>0.395</u>	0.371	0.376	0.410
	α	5.50	5.54	7.42	13.14

Note: f means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates dominant mode for each FDR.

As shown in Fig. 7-8, the Alberta, WA and CA area oscillated against CO area at the ~0.25Hz mode. Although the tripped plant is located in AZ, far from Alberta area, the Alberta unit still exhibited most significant oscillation magnitude and led this mode. For the 0.4Hz mode, the Alberta unit oscillated against CA, WA and CO areas. The red star on the map indicated the location of the tripped plant.

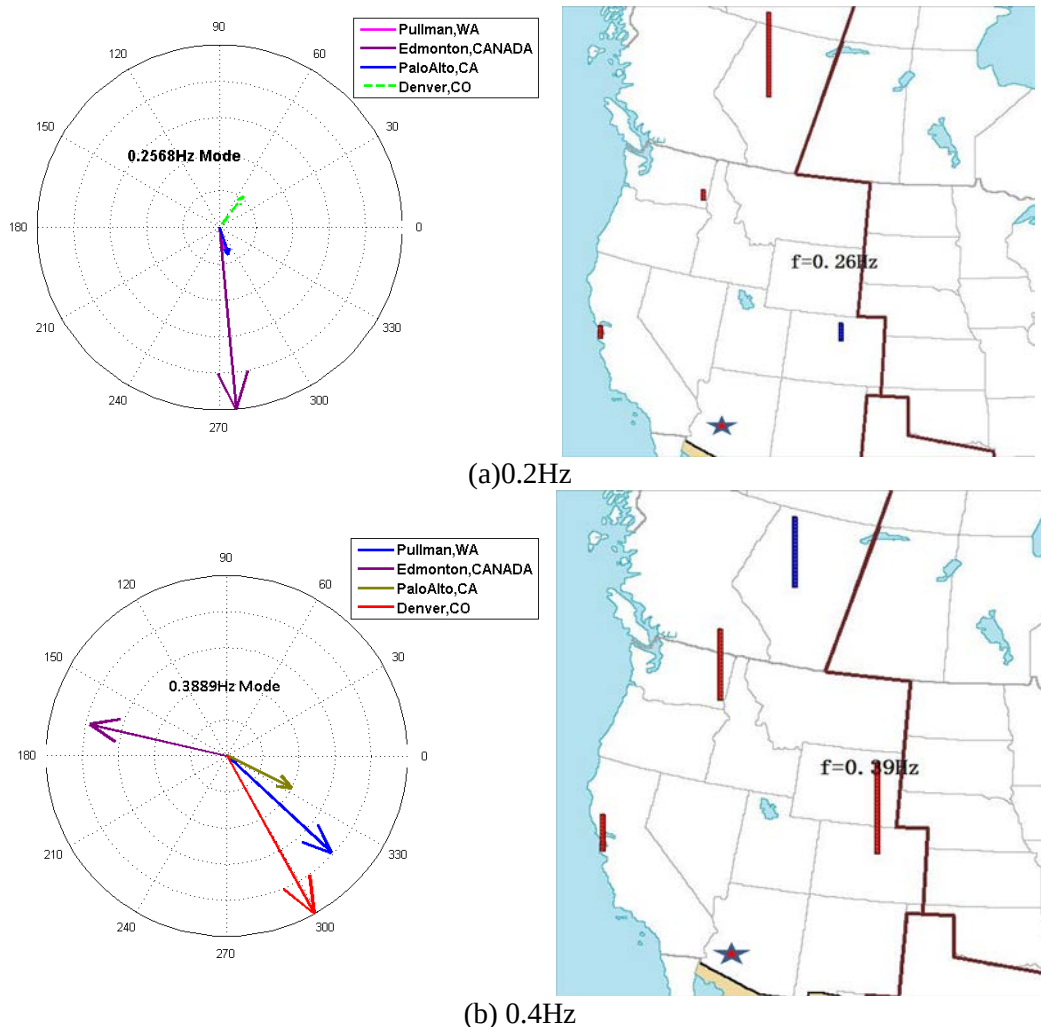


Fig. 7-8. 0.2Hz /0.4Hz mode shape of Palo Verde generation trip of 2010/06/18

7.3.2.2 Case 2: Jim Bridger Generation Trip on Nov 4, 2010

There was a trip of Jim Bridger unit in Wyoming on Nov 4, 2010, with an estimated amount of nearly 1000MW. The Jim Bridger generation plant is a coal-fired power station near Point of Rocks, Wyoming. Fig. 7-9 shows the frequency excursion and relative angle oscillation during the disturbance. The Alberta unit was not working during this disturbance.

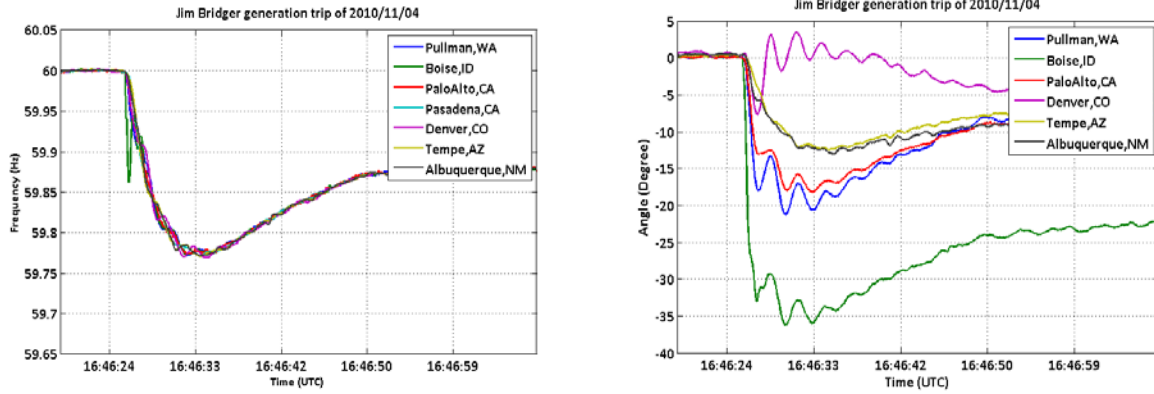


Fig. 7-9. Frequency excursion and Relative angle oscillation of Jim Bridger unit trip of 2010/11/04

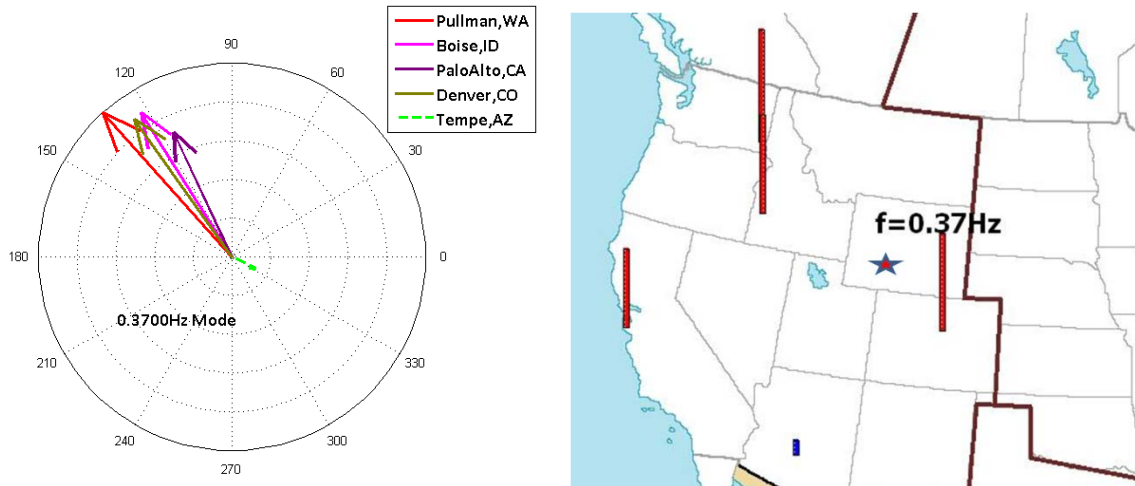
The modal analysis results from the Matrix Pencil method are listed in Table 7-3. There are two obvious modes (~ 0.4 Hz and $0.5 \sim 0.6$ Hz). The oscillation clustering pattern for each mode is shown in Fig. 7-10.

Table 7-3 Modal analysis results of Jim Bridger generation trip of 2010/11/04

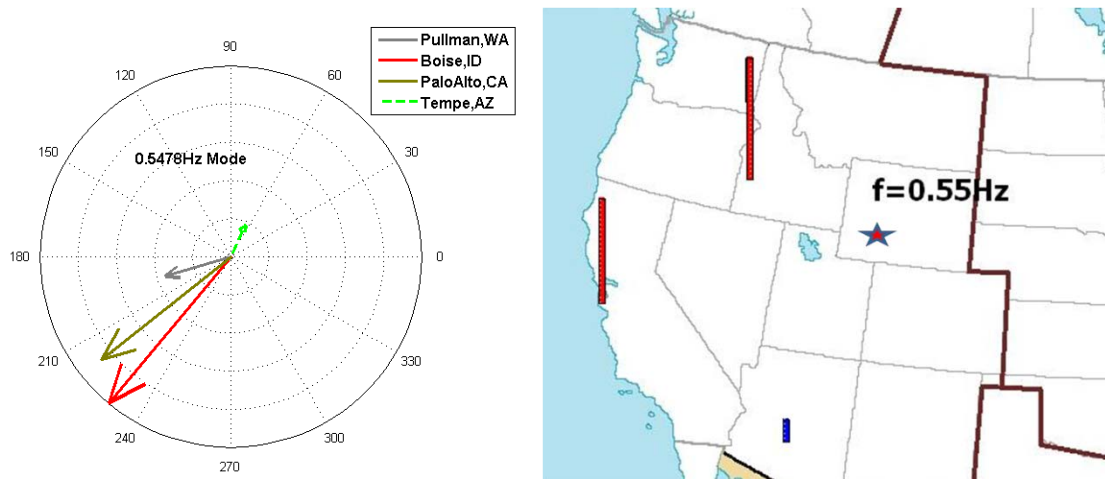
Modes (Hz)		Pullman	Denver	Palo Alto	Boise	Albuquerque	Tempe
0.4	f	0.363	0.369	0.370	0.388	-	0.358
	α	9.88	11.06	12.14	9.14	-	8.65
0.5-0.6	f	0.593	0.540	0.524	-	0.619	0.534
	α	12.10	28.03	20.91	-	15.54	40.57

Note: f means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode for each FDR.

Since there was no available data from Alberta unit during the disturbance time, the oscillation information of that area was lacked, especially for the 0.2Hz mode. For the 0.4Hz mode, AZ area oscillated against the northern and CA areas. For the 0.5-0.6Hz mode, AZ oscillates against the CA and northern areas. The red star indicated the location of tripped plant.



(a) 0.4Hz



(b) 0.5-0.6Hz

Fig. 7-10. 0.4Hz/0.5-0.6Hz mode shapes of Jim Bridger generation trip of 2010/11/04

7.3.2.3 Case 3: AESO Generation Trip on Jan 6, 2011

There was a trip of AESO Unit near Edmonton, Canada on Jan 6, 2011, with an estimated amount of 450MW. This generation trip has a smaller frequency deviation compared with other cases; however, it triggered a large oscillation on Alberta unit, which is close to the event location. The maximum peak-peak angle oscillation magnitude reaches about 30° . Fig. 7-11 shows the frequency excursion and relative angle oscillation during the disturbance.

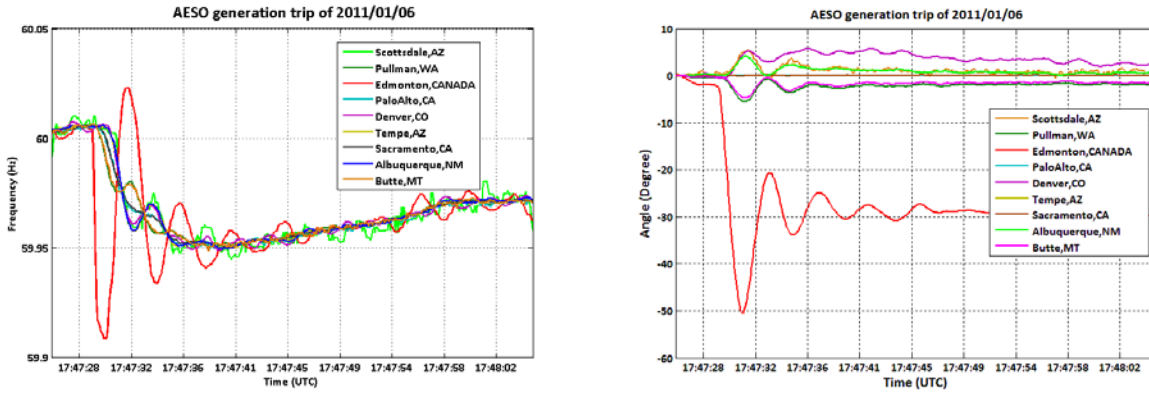


Fig. 7-11. Frequency excursion and Relative angle oscillation of AESO unit trip of 2010/07/28

The modal analysis results are listed in Table 7-4. The generation trip in AESO area incited one dominant 0.2Hz mode among all active units. The oscillation mode shape of this mode is shown in Fig. 7-12.

Table 7-4 Modal analysis results of AESO generation trip of 2011/01/06

Modes (Hz)		Pullman	Alberta	Denver	Tempe	Albuquerque	Butte
0.2	f	<u>0.261</u>	<u>0.237</u>	<u>0.248</u>	<u>0.236</u>	<u>0.251</u>	<u>0.263</u>
	α	18.91	15.61	42.12	24.65	22.86	16.80

Note: f means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode.

As shown in Fig. 7-12, the southern areas (AZ, NM, CO) oscillated against Alberta, northern areas at the dominant 0.2Hz mode. The Alberta unit exhibited a large oscillation magnitude and led the 0.2Hz mode.

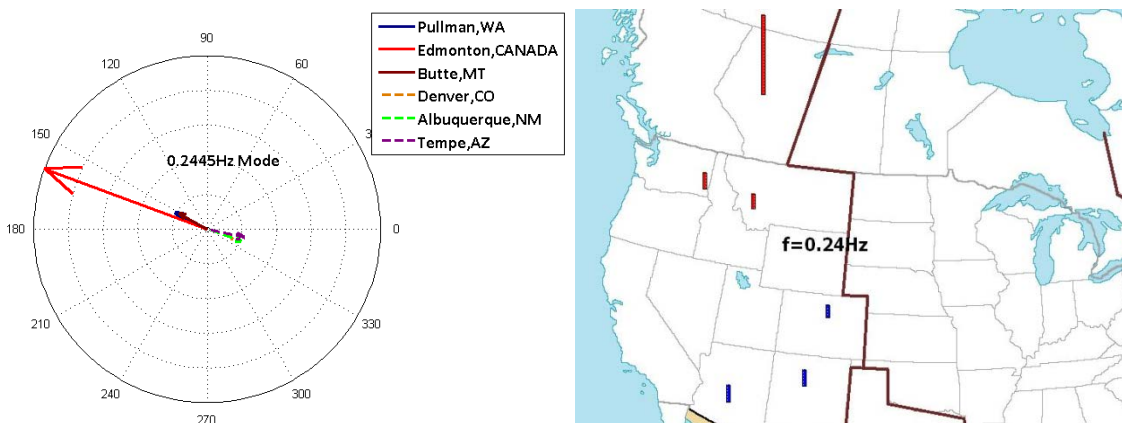


Fig. 7-12. 0.2Hz mode shape of AESO generation trip of 2011/01/06

7.3.2.4 Case 4: Diablo Canyon Generation Trip on March 26, 2011

There was a trip of Diablo Canyon unit in CA on March 26, 2011, with an estimated amount of 680MW. The Diablo Canyon generation plant is located in the southern part of California. Fig. 7-13 shows the frequency excursion and relative angle oscillation during the disturbance.

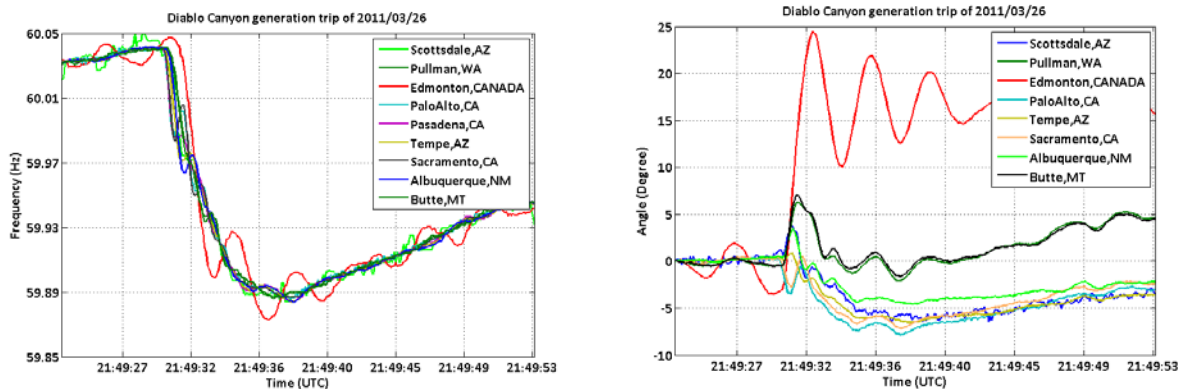


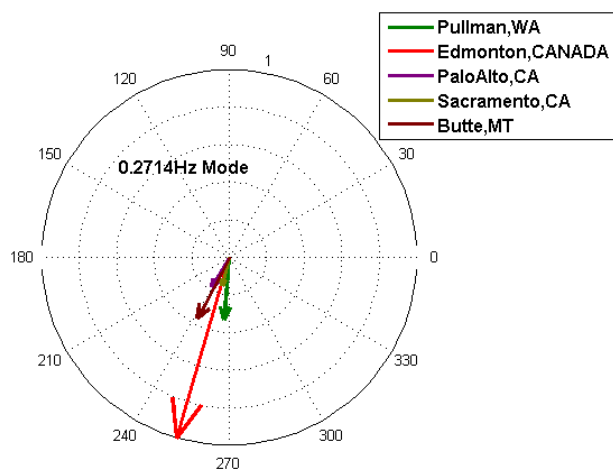
Fig. 7-13. Frequency excursion and Relative angle oscillation of Diablo Canyon generation trip of 2011/03/26

The modal analysis results are listed in Table 7-5. Several modes appeared among these active FDRs (0.2Hz, 0.3-0.4Hz, 0.5-0.6 and 0.7Hz). The oscillation clustering pattern is shown in Fig. 7-14. For the ~0.2Hz mode, the Alberta, northern and CA areas oscillated together in one cluster. The Alberta unit still exhibited most significant oscillation magnitude at 0.2Hz mode. For the 0.3-0.4Hz mode, the northern and CA areas oscillated together. For the 0.7Hz mode, the CA area oscillated against MT area. The red star on the map indicate the location of tripped plant.

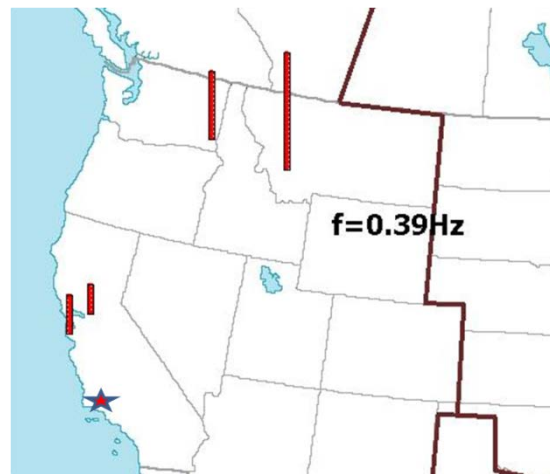
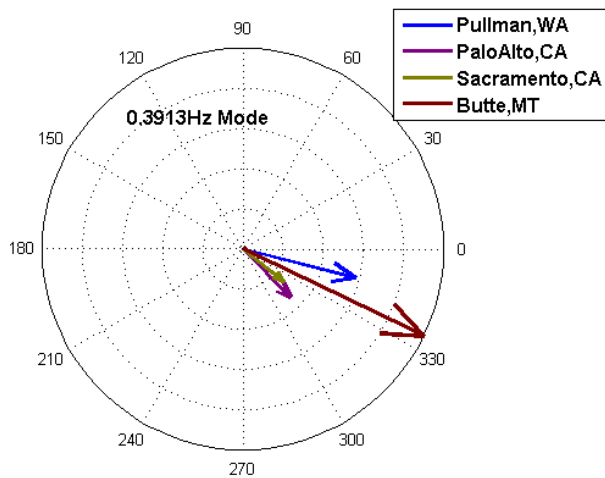
Table 7-5 Modal analysis results of Diablo Canyon generation trip of 2011/03/26

Modes (Hz)		Pullman	Alberta	Palo Alto	Tempe	Sacramento	Albuquerque	Butte
~0.2	f	<u>0.270</u>	<u>0.274</u>	<u>0.269</u>	-	<u>0.261</u>	-	<u>0.282</u>
	α	13.02	7.56	15.06	-	12.93	-	12.69
0.3-0.4	f	0.387	-	0.397	-	0.394	<u>0.320</u>	0.386
	α	12.41	-	14.22	-	11.48	14.24	18.29
0.6	f	-	-	-	0.595	-	0.576	-
	α	-	-	-	26.87	-	16.27	-
0.7	f	-	-	0.733	-	0.752	-	0.738
	α	-	-	13.05	-	12.99	-	15.23

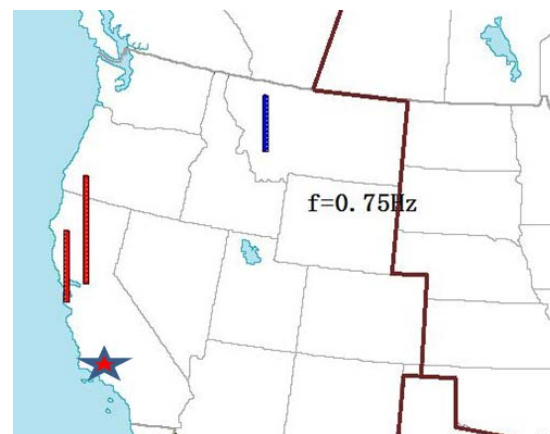
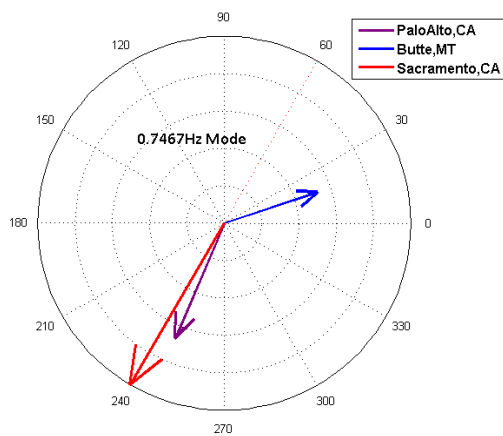
Note: *f* means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red text indicates the dominant mode for each FDR.



(a) 0.27Hz



(b) 0.39Hz



(c) 0.7Hz

Fig. 7-14. 0.2/0.4/0.7Hz mode shape of Diablo Canyon generation trip of 2011/03/26

7.3.2.5 Case 5: Mesquite Generation Trip on April 28, 2011

There was a trip of Mesquite unit in AZ on April 28, 2011, with an estimated amount of 840MW. Fig. 7-15 shows the frequency excursion and relative angle oscillation during the disturbance.

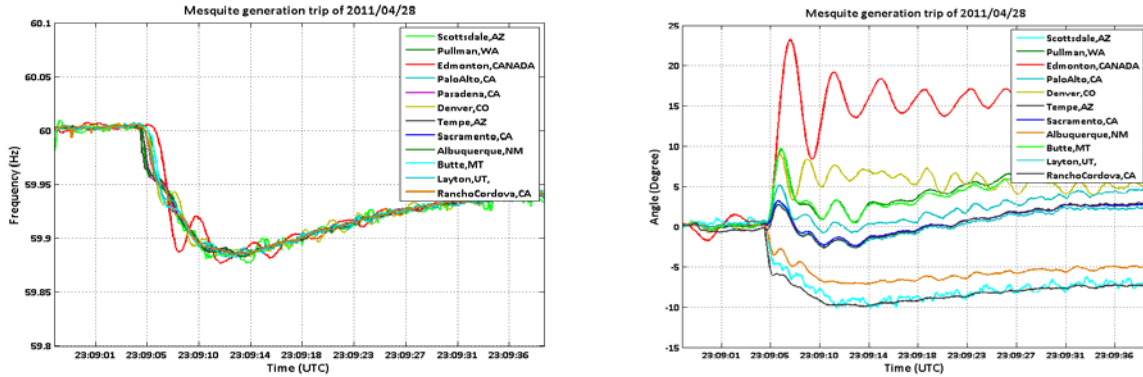


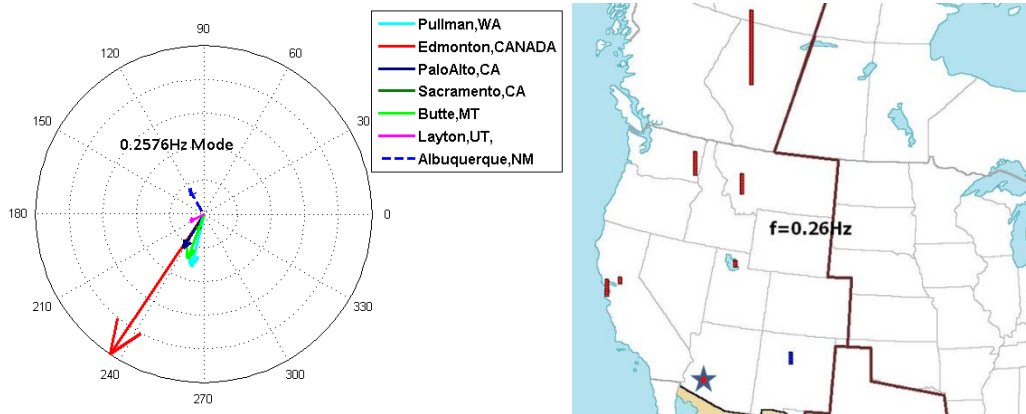
Fig. 7-15. Frequency excursion and Relative angle oscillation of Mesquite generation trip of 2011/04/28

The modal analysis results are listed in Table 7-6. The 0.2Hz and 0.4Hz modes presented as two major modes. The oscillation clustering pattern of these two modes is shown in Fig. 7-8. For the 0.2Hz mode, the Alberta, northern and CA areas oscillated against NM area. The Alberta area still exhibited most significant oscillation magnitude and led this mode. For the 0.4Hz mode, the northern, CA and CO areas oscillated together. The Alberta unit did not show obvious oscillation magnitude on this mode. Only Palo Alto and Albuquerque units show 0.55Hz oscillation mode, in which these two units oscillated against each other.

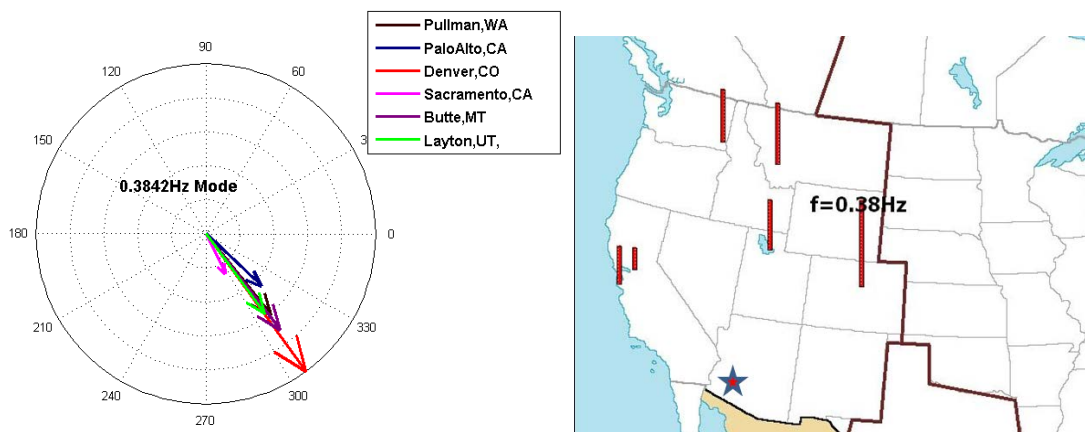
Table 7-6 Modal analysis results of Mesquite generation trip of 2011/04/28

Modes (Hz)		Pullman	Alberta	Palo Alto	Denver	Albuquerque	Sacramento	Butte	Layton
0.2	f	<u>0.251</u>	<u>0.257</u>	<u>0.258</u>	-	0.272	0.248	0.255	0.272
	α	14.54	11.15	24.17	-	30.13	14.23	13.62	9.95
0.4	f	0.381	-	0.370	<u>0.404</u>	-	<u>0.382</u>	<u>0.382</u>	<u>0.388</u>
	α	8.99	-	12.41	11.83	-	7.83	10.16	13.72
0.5-0.6	f	-	-	0.565	-	<u>0.536</u>	-	-	-
	α	-	-	19.97	-	25.93	-	-	-

Note: *f* means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode of each FDR.



(a) 0.2Hz



(b) 0.4Hz

Fig. 7-16. 0.2Hz/0.4Hz mode shapes of Mesquite generation trip of 2011/04/28

7.3.2.6 Case 6: Colstrip Trip on Aug 10, 2011

There was a trip of Colstrip unit in Montana on Aug 10, 2011, with an estimated amount of nearly 1400MW. Fig. 7-17 shows the frequency excursion and relative angle oscillation during the disturbance.

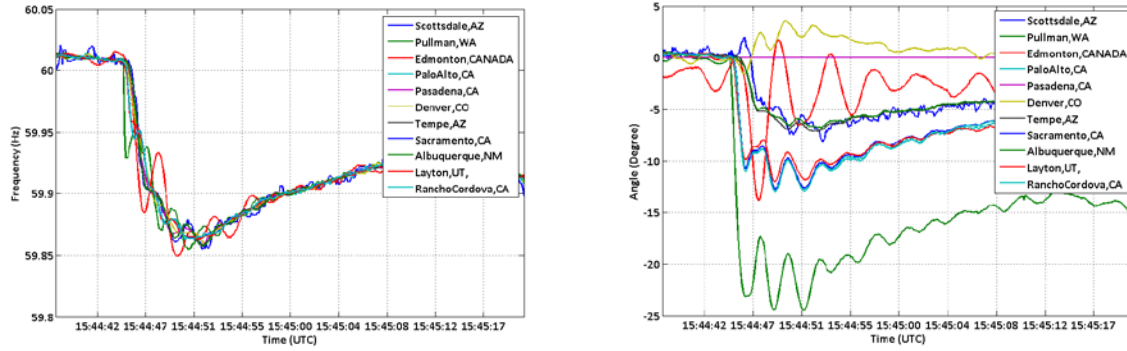


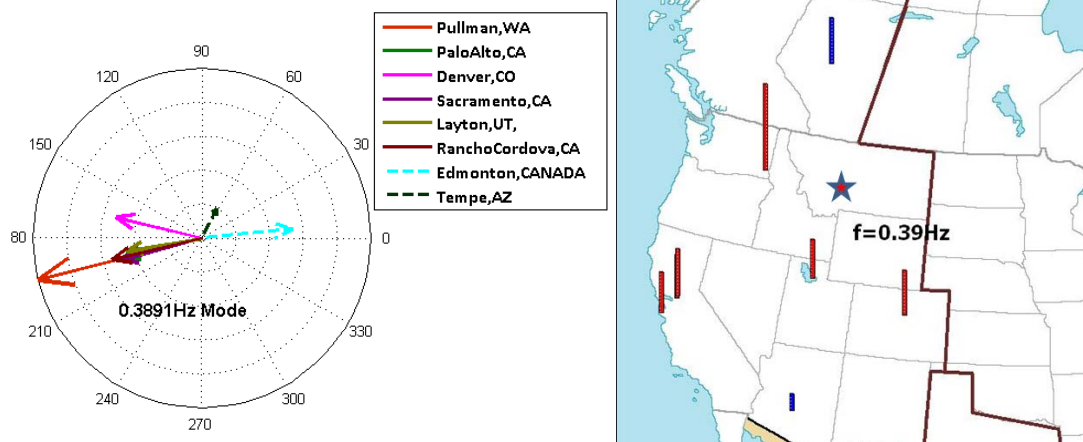
Fig. 7-17. Frequency excursion and Relative angle oscillation of Colstrip unit trip of 2011/08/10

The modal analysis results are listed in Table 7-7. There are three major modes ($\sim 0.2\text{Hz}$, $\sim 0.4\text{Hz}$ and $\sim 0.6\text{Hz}$). The most common mode among all these active FDRs is 0.4Hz mode. As shown in Fig. 7-18, the Alberta unit oscillated against the northern, CO and CA areas at 0.4Hz mode. The unit in WA exhibited largest oscillation magnitude and led this mode. For the 0.6Hz mode, the WA, CA and UT areas oscillated together.

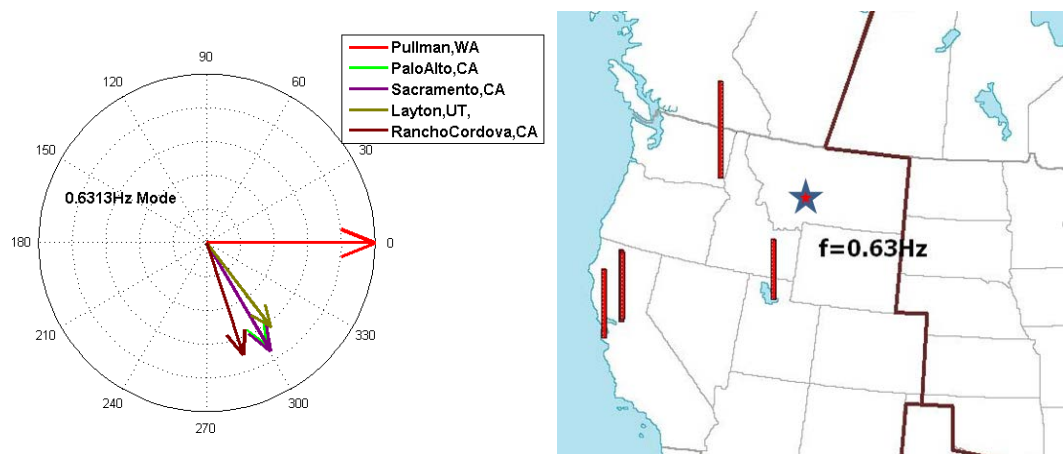
Table 7-7 Modal analysis results of Colstrip generation trip of 2011/08/10

Modes (Hz)		Pullman	Alberta	Denver	Layton	Rancho Cordova	Palo Alto	Sacramento	Albuquerque	Tempe
0.2	f	0.237	0.237	-	-	-	-	-	0.207	0.217
	α	1.09	7.78	-	-	-	-	-	32.83	35.27
0.4	f	0.390	0.379	0.414	0.390	0.384	0.387	0.385	-	0.383
	α	8.50	8.76	14.80	8.25	8.48	8.17	7.98	-	9.83
0.6-	f	0.623	-	-	0.646	0.632	0.632	0.623	-	-
0.7	α	27.80	-	-	12.04	15.86	14.40	14.85	-	-

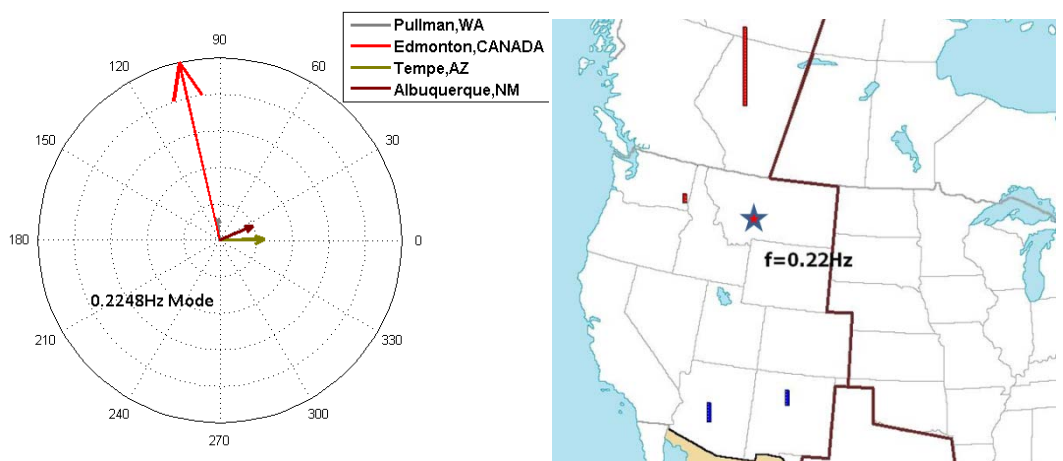
Note: *f* means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode of each FDR.



(a) 0.4Hz



(b) 0.6Hz



(c) 0.2Hz

Fig. 7-18. 0.2/0.4/0.6Hz mode shape of Colstrip generation trip of 2011/08/10

7.3.2.7 Case 7: Colstrip Trip on Aug 29, 2011

Another Colstrip unit trip in Montana occurred on Aug 29, 2011, with an estimated amount of 760MW. Fig. 7-19 shows the frequency excursion and relative angle oscillation during the disturbance.

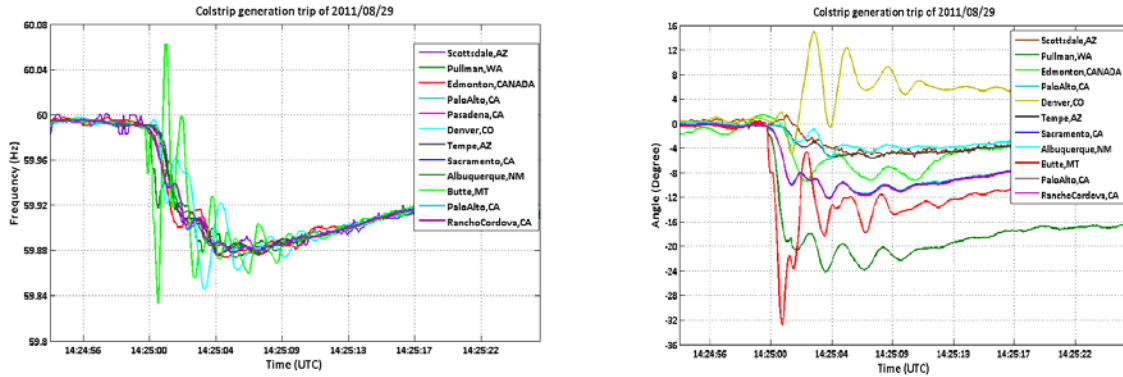


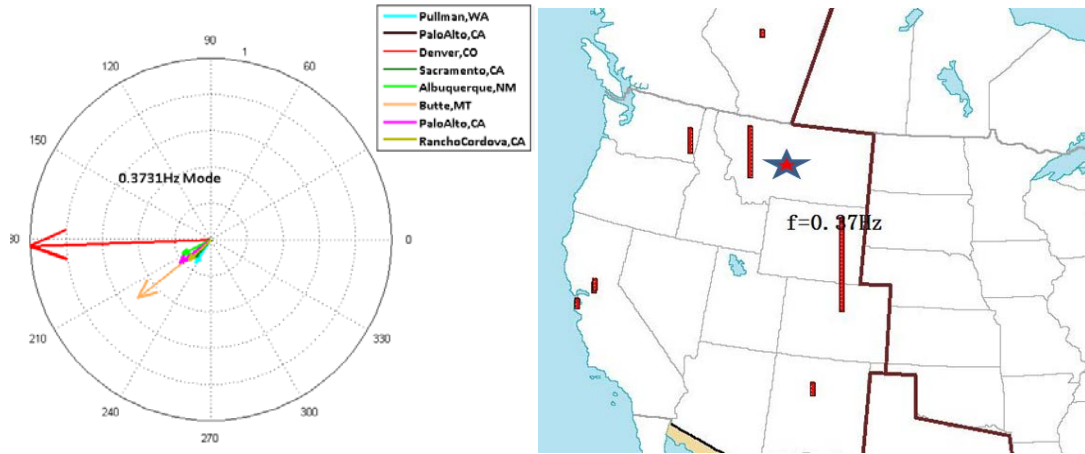
Fig. 7-19. Frequency excursion and Relative angle oscillation of Colstrip generation trip of 2011/08/29

The modal analysis results are listed in Table 7-8. There are three major modes (~ 0.2 Hz, ~ 0.4 Hz and ~ 0.6 Hz). The most common modes among all these active FDRs re 0.4Hz and 0.6Hz modes. As shown in Fig. 7-18, all the active units oscillated together at 0.4Hz mode. The unit in CO exhibited largest oscillation magnitude and led this mode.

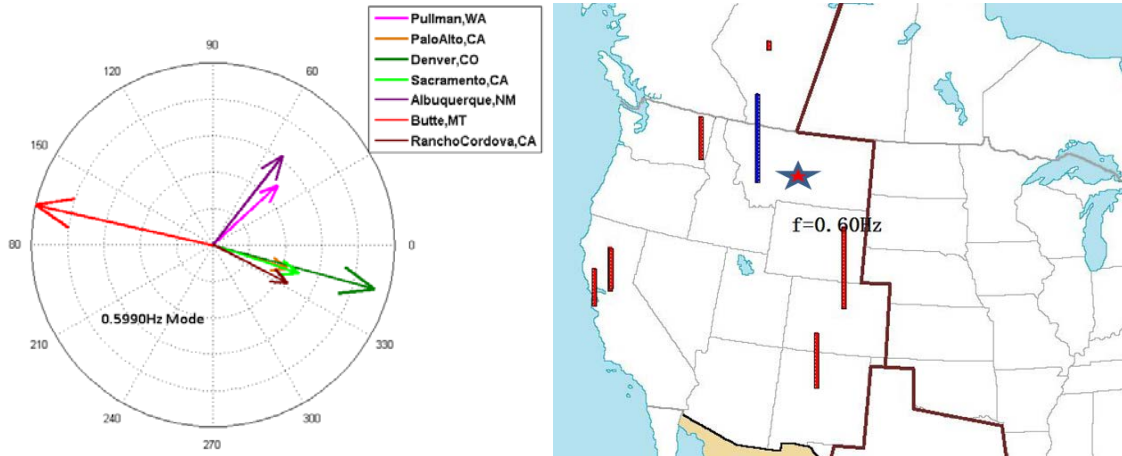
Table 7-8 Modal analysis results of Colstrip generation trip of 2011/08/29

Modes (Hz)		Pullman	Alberta	Denver	Rancho Cordova	Palo Alto	Albuquerque	Sacramento	Butte
0.2	f	0.291	0.267	0.324	-	-	-	-	0.282
	α	15.92	8.88	14.31	-	-	-	-	21.95
0.4	f	0.381	0.365	0.380	0.373	0.373	0.372	0.372	0.376
	α	8.16	10.45	13.64	7.43	7.21	10.86	7.08	10.65
0.6	f	0.603	-	0.579	0.613	0.608	0.582	0.606	0.581
	α	12.14	-	6.77	9.42	9.61	13.88	10.26	5.71

Note: *f* means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode of each FDR.



(a) 0.4Hz



(b) 0.6Hz

Fig. 7-20. 0.4/0.6Hz mode shape of Colstrip generation trip of 2011/08/29

7.3.2.8 Summary

1. The summary of the above oscillation cases is shown in Table 7-9. Four modes appear in these oscillation cases triggered by generation trips: $\sim 0.2\text{Hz}$, $0.35\text{-}0.4\text{Hz}$, ~ 0.6 and $\sim 0.7\text{Hz}$. However, not all four modes appear simultaneously for each case, depending on the disturbance. The modes observed are generally consistent with the principle modes identified by many other tests and applications in WAMS [27]- [32].

2. The oscillation magnitude is not necessarily proportional to the generation trip amount. Oscillation magnitude depends on factors such as: system topology, load distribution at the tripping time, the tripped generation plant location, its relative location to measurement units, etc.

3. The 0.2Hz mode is referred to as NS (north-south) mode in [27][28][29]. The mode frequency may span from 0.22Hz to 0.28Hz. The Alberta unit usually exhibits most significant oscillation magnitude on this mode. And the most common mode shape for 0.2Hz mode is the Alberta, northern and CA areas oscillate against the southeastern areas as shown in Fig. 7-21. It is probably caused by the long transmission inter-tie between Alberta and the remainder of the western power system [32]. Especially when the generation unit trips in AESO, it will incite a large oscillation (0.2Hz) on Alberta unit, like in Case 3.

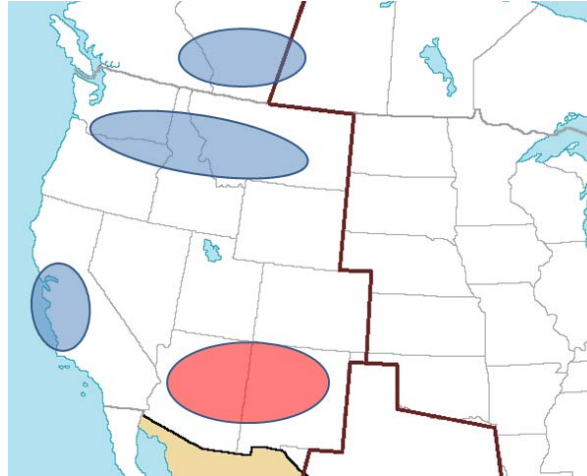


Fig. 7-21. Common mode shape for 0.2Hz mode

4. The ~ 0.4 Hz mode is referred to as the Alberta mode in [27][28][29]. For the 0.4Hz mode, the most common mode shape is the Alberta area oscillates against the northern, CA areas, as shown in Fig. 7-22.

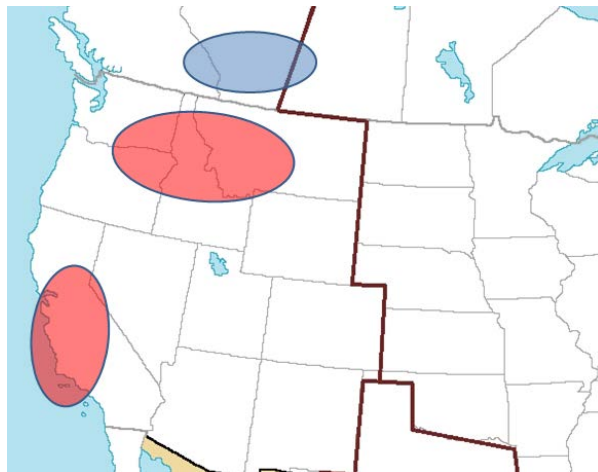


Fig. 7-22. Common mode shape for 0.4Hz mode

5. The 0.7 Hz or 0.6Hz mode is not as common as the other two.

Table 7-9 Summary of oscillation analysis results of generation trips

Cases	Mode Frequency (Hz)	Mode Shape
Case 1	0.2-0.3	Alberta&Northern&CA areas vs CO
	0.35-0.4	Alberta vs Northern&CA&CO areas
Case 2	0.35-0.4	AZ vs CO&CA&Northern areas
	0.5-0.6	AZ vs CA&Northern areas
Case 3	0.2-0.3	Southern areas vs northern&CA areas
Case 4	0.2-0.3	Alberta &Northern&CA areas
	0.35-0.4	Northern & CA areas
	0.7	MT vs CA
Case 5	0.2-0.3	Alberta &Northern&CA&UT areas
	0.35-0.4	Northern&CA&UT&CO areas
	0.55Hz	CA vs NM area
Case 6	0.2-0.3	Alberta&WA
	0.35-0.4	Alberta& AZ vs Northern&CA&UT&CO
	0.6	CA&UT
Case 7	0.35-0.4	Alberta&Northern&CO&CA
	0.6	MT vs CA&WA&southeastern areas

7.3.3 Line Trip

The line trip will also incite oscillations as the generation trips. However, different from the generation trips in which the system frequency will experience a significant decline due to the generation drop, the line trip disturbance usually will cause the frequencies rise or drop at different locations.

7.3.3.1 Line Trip with Alberta Connected

- **Case 1: Line trip with Alberta Connected on March 31, 2011**

The frequency excursion and relative angle for the line trip on Mar 31, 2011 is shown in Fig. 7-23. Table 7-10 summarizes the modal analysis results of this line trip disturbance. Three major modes appeared: 0.2Hz, 0.4Hz, and 0.6-0.7Hz. The most common mode among these active FDRs is 0.4Hz mode, while the 0.2Hz is still the dominant mode for the Alberta unit. The mode shapes for the 0.2Hz and 0.4Hz are shown in Fig. 7-24.

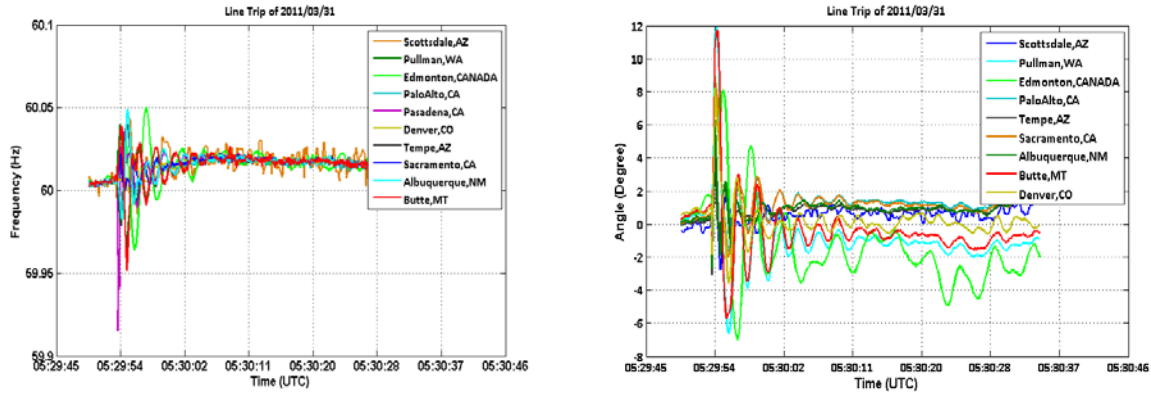


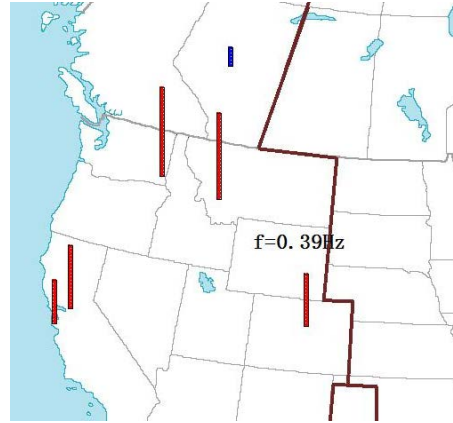
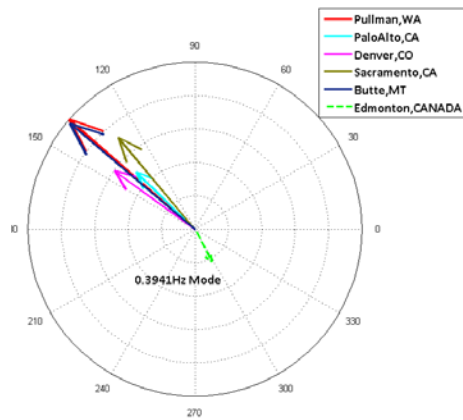
Fig. 7-23. Frequency excursion and Relative angle oscillation of line trip of 2011/03/31

Table 7-10 Modal analysis results of line trip of 2011/03/31

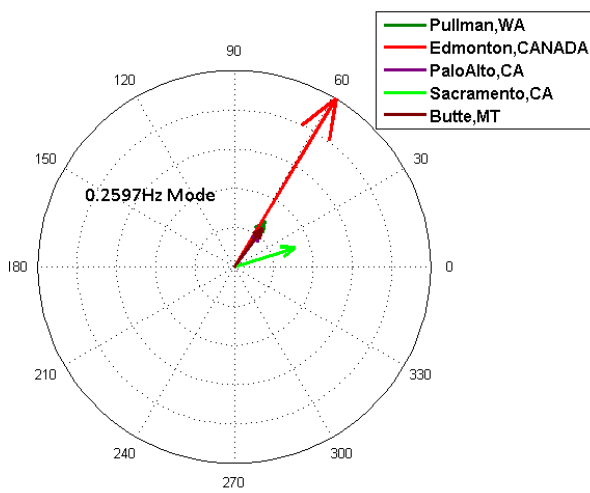
Modes (Hz)		Pullman	Alberta	Palo Alto	Denver	Sacramento	Albuquerque	Butte
0.4	<i>f</i>	<u>0.396</u>	0.398	<u>0.392</u>	<u>0.387</u>	<u>0.394</u>	-	<u>0.395</u>
	<i>a</i>	9.87	7.19	9.82	13.49	12.33	-	9.78
0.2-0.3	<i>f</i>	0.256	<u>0.249</u>	0.250	-	0.286	-	0.256
	<i>a</i>	18.06	14.33	28.02	-	25.85	-	17.15
0.6-0.7	<i>f</i>	-	-	-	-	0.660	<u>0.607</u>	-
	<i>a</i>	-	-	-	-	11.62	13.16	-

Note: *f* means damping frequency in Hz; *a* means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode of each FDR.

As shown in Fig. 7-24, for the 0.4Hz mode, the Alberta area oscillated against the northern, CA and CO areas. And the FDR units located in northern areas (MT, WA) exhibited largest oscillation magnitudes and led this mode. For 0.2Hz mode, the Alberta, the northern and CA areas oscillated together.



(a)0.4Hz Mode



(b)0.2Hz Mode

Fig. 7-24. 0.2/0.4Hz mode shape of line trip of 2011/03/31

- **Case 2: Line trip with Alberta Connected on June 04, 2011**

The frequency excursion and relative angle for the line trip is shown in Fig. 7-25.

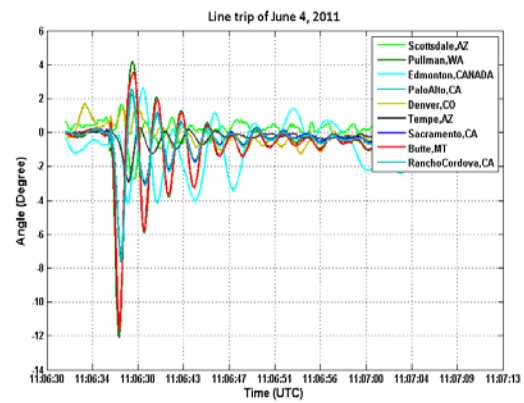
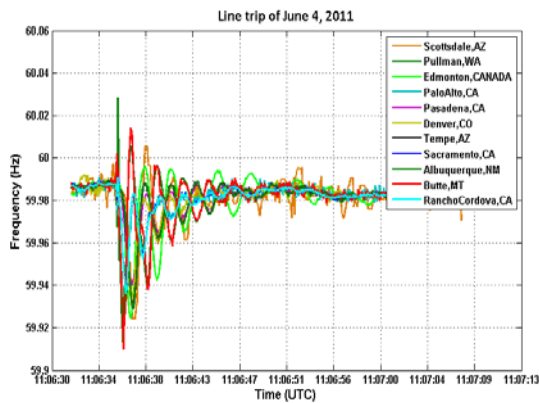


Fig. 7-25. Frequency excursion and Relative angle oscillation of line trip of 2011/06/04

Table 7-11 summarizes the modal analysis results of this line trip disturbance. The most common dominant mode for all active FDRs is 0.4Hz. Even for the Alberta unit, the dominant mode is 0.4Hz instead of 0.2Hz in this line trip cases. The oscillation mode shape for 0.4Hz mode is shown in Fig. 7-26. For the 0.4Hz mode, the Alberta and southeastern area oscillated against northern and CA areas.

Table 7-11 Modal analysis results of line trip of 2011/06/04

Mode(Hz)		Pullman	Alberta	Palo Alto	Denver	Tempe	Sacramento	Albuquerque	Butte	Rancho Cordova
0.4	f	<u>0.427</u>	<u>0.428</u>	<u>0.422</u>	-	<u>0.427</u>	<u>0.423</u>	<u>0.431</u>	<u>0.428</u>	<u>0.425</u>
	a	7.64	8.56	7.83	-	6.26	7.90	6.42	7.86	7.39
0.2-0.3	f	-	0.290	-	<u>0.251</u>	-	-	-	-	-
	a	-	-0.38	-	51.33	-	-	-	-	-
0.6-0.7	f	-	-	-	-	0.694	-	0.684	-	0.671
	a	-	-	-	-	16.13	-	12.74	-	49.90
0.8	f	0.875	-	-	-	-	-	-	0.874	-
	a	12.76	-	-	-	-	-	-	12.08	-

Note: f means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode of each FDR.

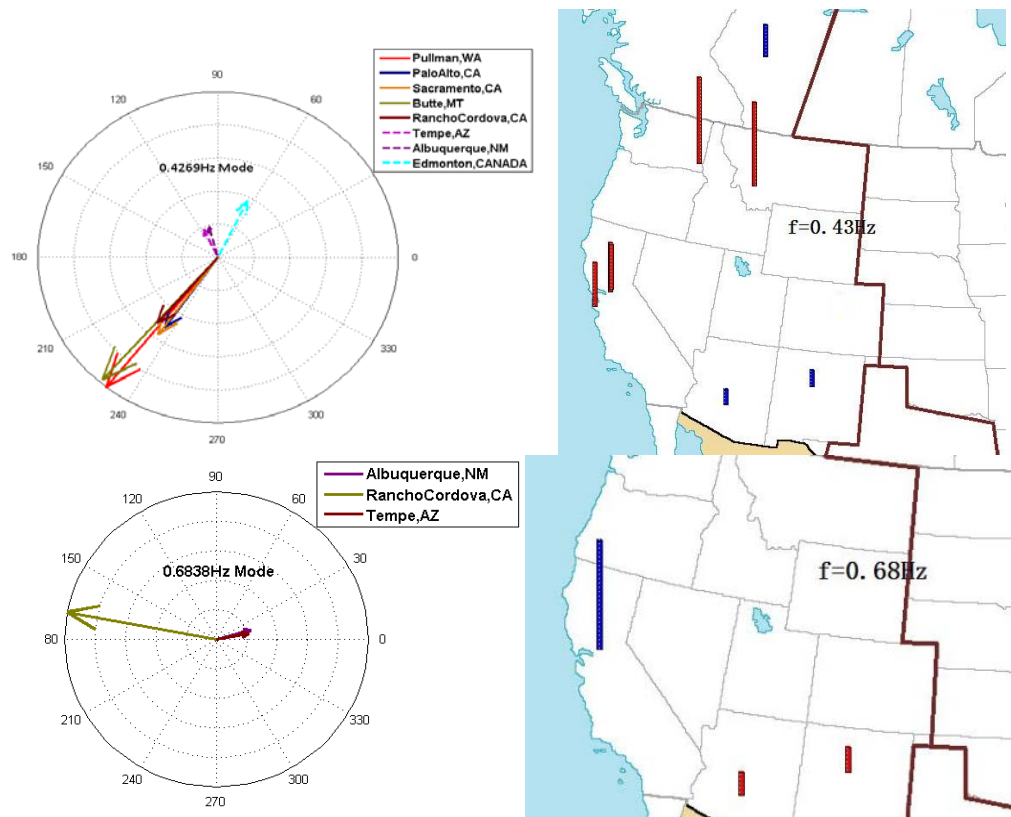


Fig. 7-26. 0.4Hz/0.6Hz mode shape of line trip of 2011/06/04

- **Case 3: Line trip with Alberta Connected on June 18, 2011**

The frequency excursion and relative angle for the line trip on June 18, 2011 is shown in Fig. 7-27. Table 7-12 summarizes the modal analysis results of this line trip disturbance.

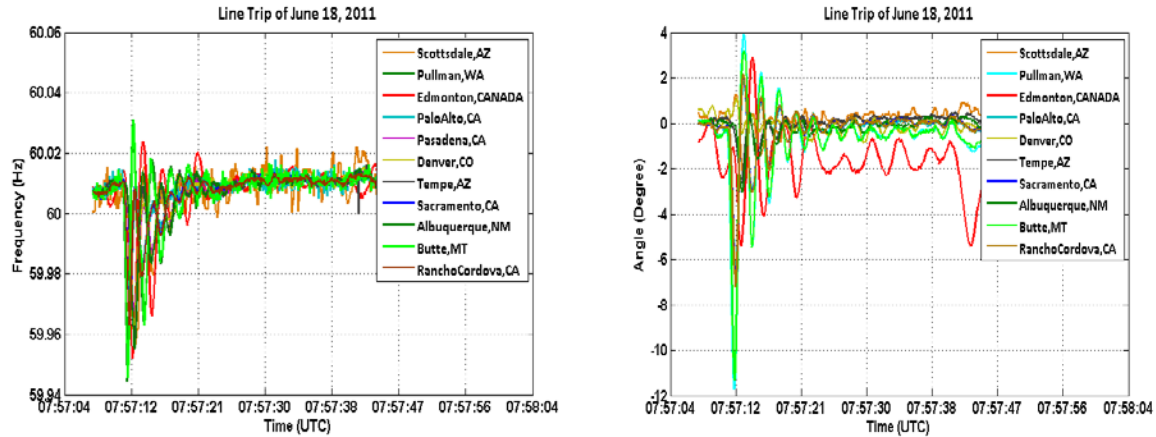


Fig. 7-27. Frequency excursion and Relative angle oscillation of line trip of 2011/06/18

Table 7-12 Modal analysis results of line trip of 2011/06/18

Modes (Hz)		Pullman	Alberta	Palo Alto	Sacramento	Albuquerque	Butte	Rancho Cordova
0.4	<i>f</i>	<u>0.432</u>	0.424	<u>0.427</u>	<u>0.427</u>	<u>0.433</u>	<u>0.430</u>	<u>0.427</u>
	<i>a</i>	8.88	7.84	9.68	9.36	10.29	9.54	8.98
0.2-0.3	<i>f</i>	-	<u>0.254</u>	-	-	-	0.264	-
	<i>a</i>	-	<u>5.76</u>	-	-	-	30.69	-
0.7	<i>f</i>	-	-	-	-	0.729	-	-
	<i>a</i>	-	-	-	-	14.17	-	-

Note: *f* means damping frequency in Hz; *a* means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode of each FDR.

There are three modes appearing during the line trip: 0.4Hz, 0.2-0.3Hz and 0.7Hz. The most common dominant mode among is 0.4Hz mode. The mode shape for the 0.4Hz mode is shown in Fig. 7-28, in which Alberta and southeastern area oscillated against northern and CA areas. And the FDR units located in northern area (MT, WA) presented largest oscillation magnitudes and led this mode. The 0.7Hz mode only appeared on the unit in Albuquerque, NM.

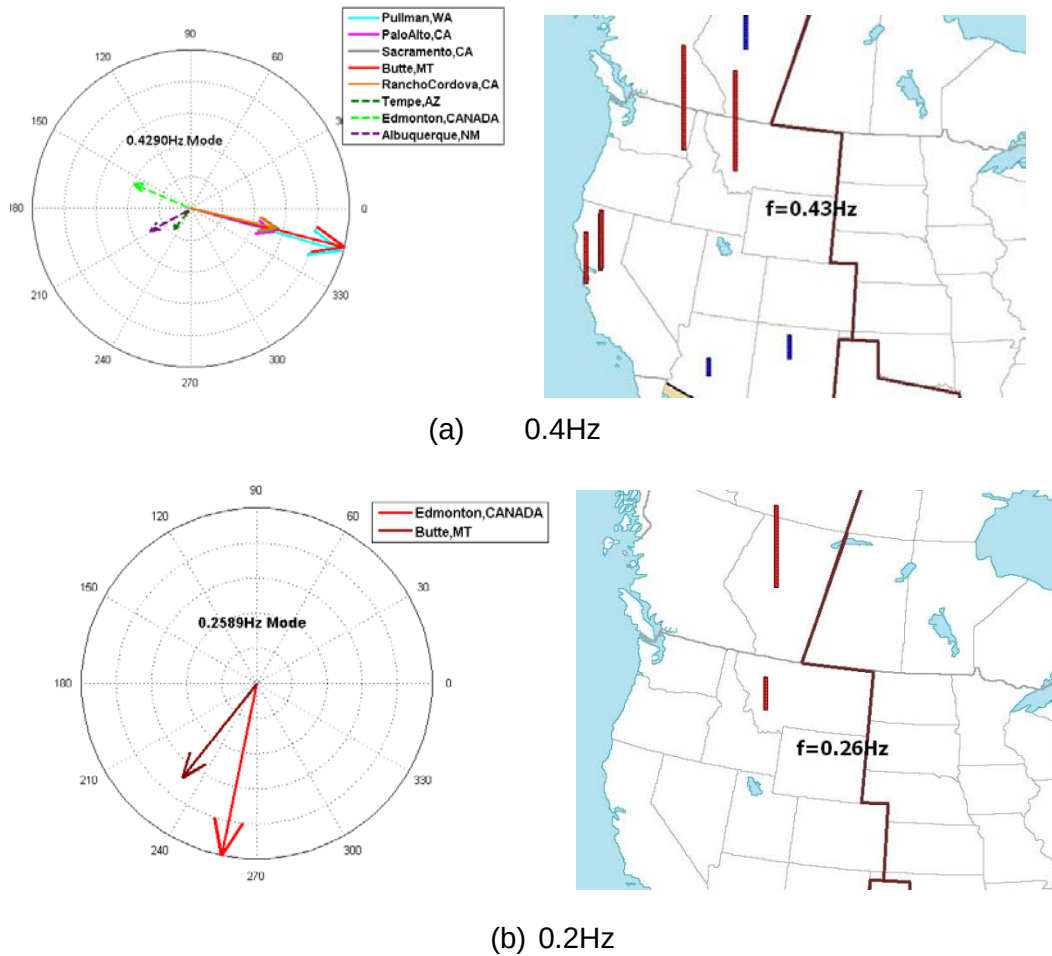


Fig. 7-28. 0.2/0.4Hz mode shape of line trip of 2011/06/18

- **Case 4: Line trip with Alberta Connected on May 11, 2011**

The frequency excursion and relative angle for the line trip on Mar 31, 2011 is shown in Fig. 7-29. Table 7-13 summarizes the modal analysis results of this line trip disturbance.

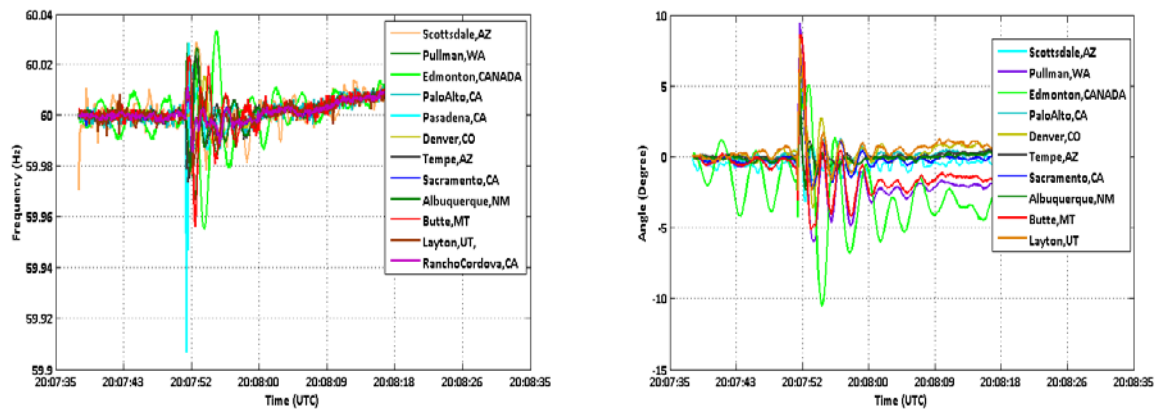


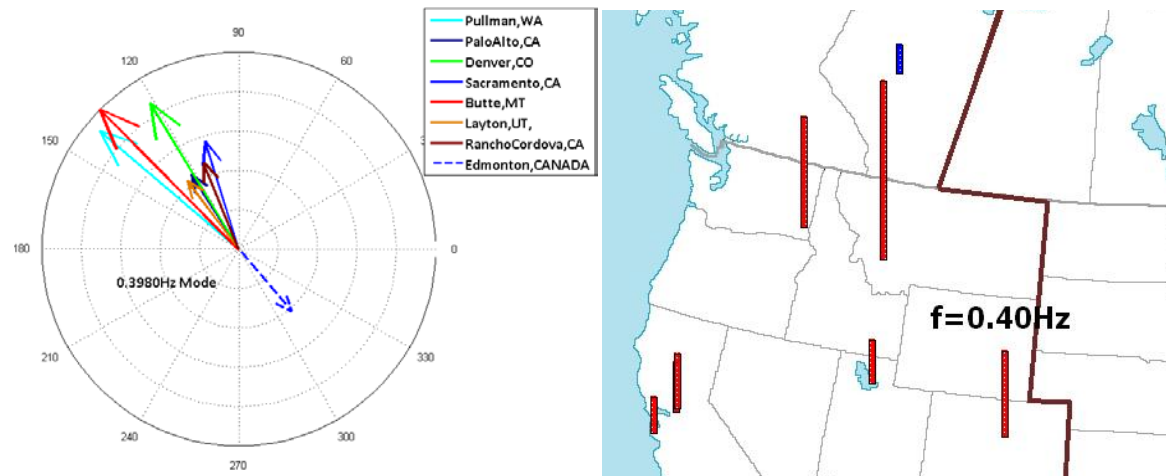
Fig. 7-29. Frequency excursion and Relative angle oscillation of line trip of 2011/05/11

Three modes appeared: 0.2Hz, 0.4Hz, and 0.8Hz. The most common mode is 0.4Hz mode, while the 0.2Hz is still the dominant mode for the Alberta unit. The mode shapes for the 0.4Hz are shown in Fig. 7-30. For 0.4Hz mode, the Alberta area oscillated against the other areas.

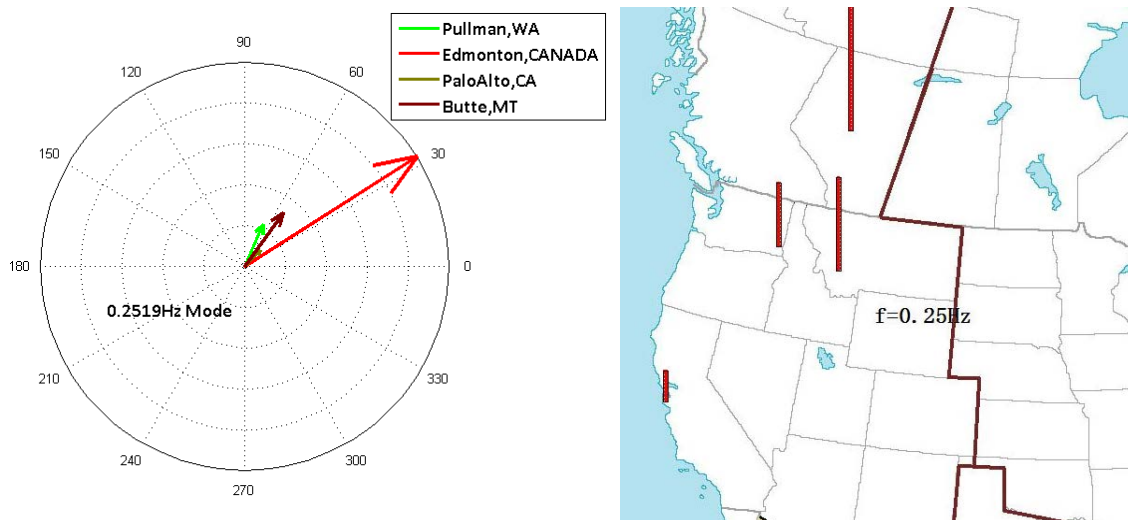
Table 7-13 Modal analysis results of line trip of 2011/05/11

Modes (Hz)		Pullman	Alberta	Palo Alto	Denver	Sacramento	Butte	Layton	Rancho Cordova
0.4	<i>f</i>	<u>0.392</u>	0.382	<u>0.396</u>	<u>0.415</u>	<u>0.404</u>	<u>0.393</u>	<u>0.397</u>	<u>0.405</u>
	<i>a</i>	8.70	9.99	8.37	15.00	10.10	9.34	7.17	8.52
0.2-0.3	<i>f</i>	0.250	<u>0.262</u>	0.242	-	-	0.253	-	-
	<i>a</i>	9.28	7.68	13.91	-	-	15.32	-	-
0.8	<i>f</i>	-	-	-	-	-	0.87	-	-
	<i>a</i>	-	-	-	-	-	16.95	-	-

Note: *f* means damping frequency in Hz; *a* means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red text indicates the dominant mode.



(a) 0.4Hz



(b) 0.2Hz

Fig. 7-30. 0.2/0.4Hz mode shape of line trip of 2011/05/11

- **Case 5: Line trip with Alberta Connected on June 25, 2011**

The frequency excursion and relative angle for the line trip on June 25, 2011 is shown in Fig. 7-31. Table 7-14 summarizes the modal analysis results of this line trip disturbance.

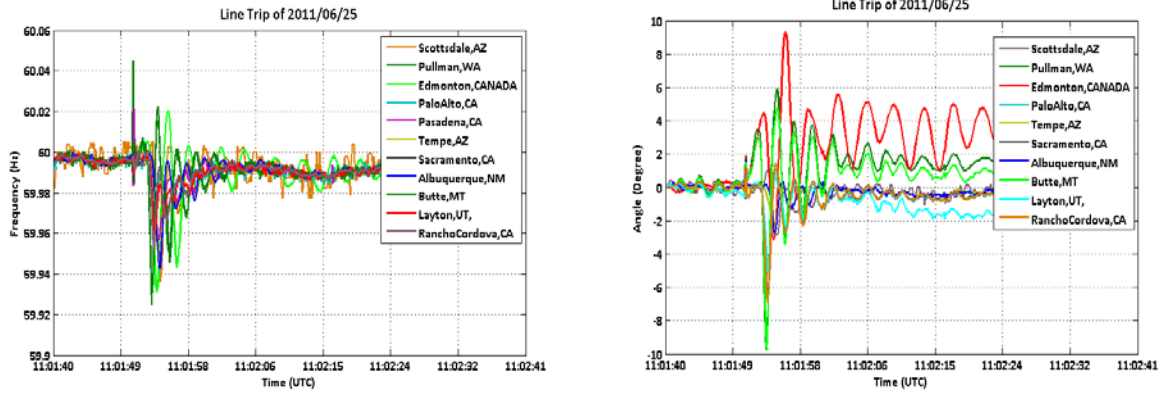


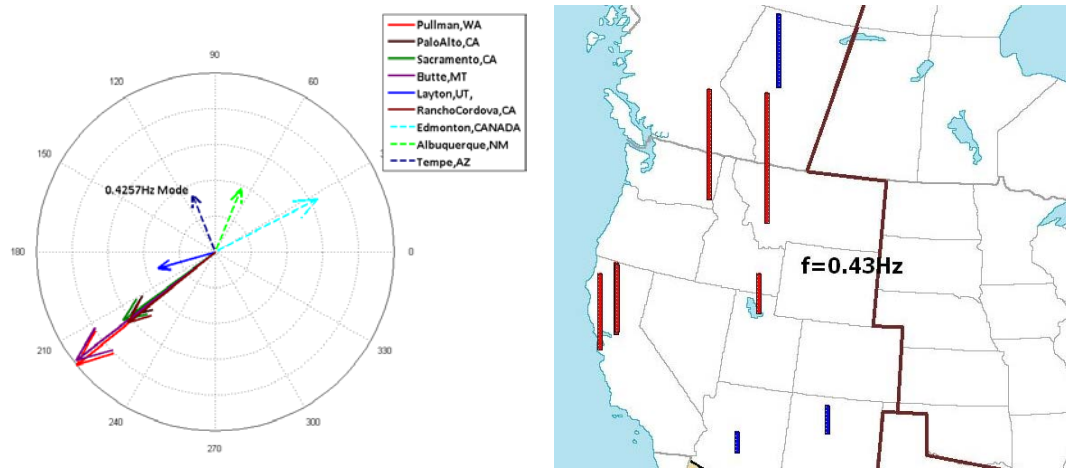
Fig. 7-31. Frequency excursion and Relative angle oscillation of line trip of 2011/06/25

Three modes appeared in this line trip disturbance: 0.2-0.3Hz, 0.4Hz and 0.8Hz. The most common mode among these active FDRs is 0.4Hz mode. The mode shape for the 0.4Hz is shown in Fig. 7-32. For 0.4Hz mode, the Alberta and southeastern areas (CO, NM) oscillated against northern and CA areas. And the FDR units located in Northern area (MT, WA) exhibited largest oscillation magnitudes and led this mode.

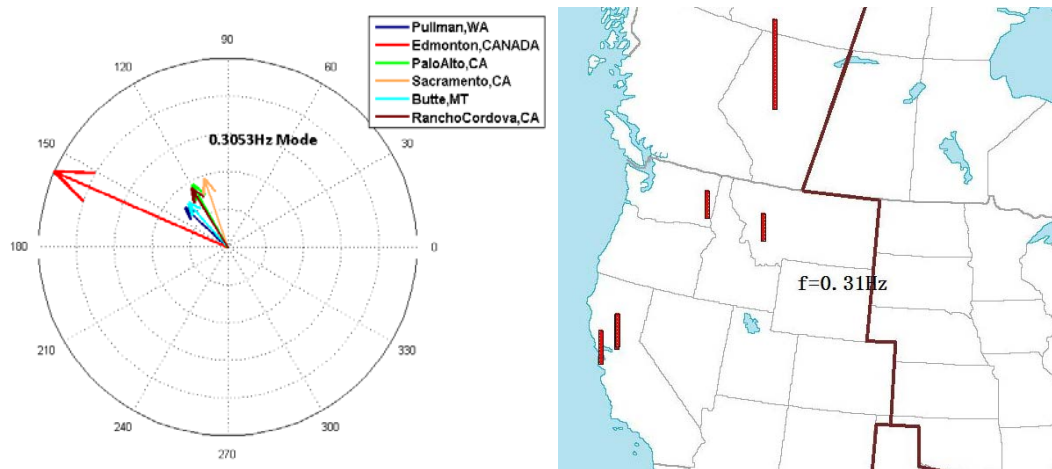
Table 7-14 Modal analysis results of line trip of 2011/06/25

Modes (Hz)		Pullman	Alberta	Palo Alto	Tempe	Sacramento	Albuquerque	Butte	Layton	Rancho Cordova
0.4	<i>f</i>	<u>0.429</u>	<u>0.421</u>	<u>0.425</u>	<u>0.416</u>	<u>0.425</u>	<u>0.426</u>	<u>0.429</u>	<u>0.434</u>	<u>0.424</u>
	<i>a</i>	<u>8.99</u>	<u>12.76</u>	<u>11.34</u>	<u>12.15</u>	<u>11.24</u>	<u>15.36</u>	<u>9.57</u>	<u>8.12</u>	<u>10.97</u>
0.2-0.3	<i>f</i>	0.302	0.290	0.309	-	0.310	-	-	-	0.308
	<i>a</i>	4.11	3.07	15.18	-	13.58	-	-	-	13.93
0.8	<i>f</i>	0.889	-	-	0.805	-	-	0.886	0.842	-
	<i>a</i>	17.66	-	-	49.29	-	-	19.37	12.57	-

Note: *f* means damping frequency in Hz; *a* means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red font indicates the dominant mode of each FDR.



(a)0.4Hz



(b)0.3Hz

Fig. 7-32. 0.4Hz/0.3Hz mode shape of line trip of 2011/06/25

7.3.3.2 Line Trip with Alberta Separated

In this section, the Type-II line trips are analyzed, in which the Alberta system is islanded from the remainder of the grid. The inter-area mode may shift in these non-typical line trip events.

- **Case 1: Alberta Separation on June 1, 2010**

One line trip event occurred on June 1, 2010, which disconnected Alberta from other parts of WECC system. The frequency excursion and relative angle oscillation is shown in Fig. 7-33. The angle dramatically separated into two groups. Taking all FDR data except the Alberta unit as modal analysis inputs, the modal analysis results are listed in Table 7-15. There are only two FDRs available for modal analysis excluding the noisy measurement from Scottsdale, AZ.

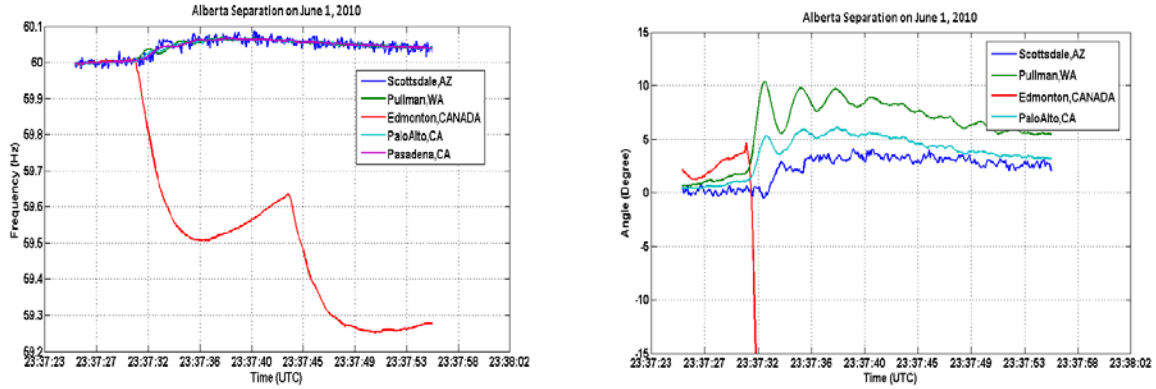


Fig. 7-33 Frequency excursion and Relative angle oscillation of Alberta separation of 2010/06/01

As shown in Table 7-15, the only dominate mode is observed around 0.3Hz instead of 0.2Hz or 0.4Hz in previous line trip cases. The FDR unit in Pullman, WA exhibited the most significant oscillation magnitude; it is probably caused by its close proximity to the islanding area.

Table 7-15 Modal analysis results of Alberta separation of 2010/06/01

Modes (Hz)		Pullman	Palo Alto
0.3	f	<u>0.342</u>	<u>0.345</u>
	α	9.23	11.28

Note: f means damping frequency in Hz; α means damping ratio in %; ‘-’ means this mode is not available or with small oscillation magnitudes. Red text indicates the dominant mode.

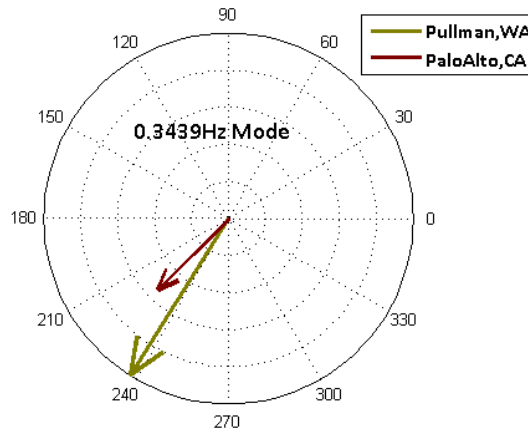


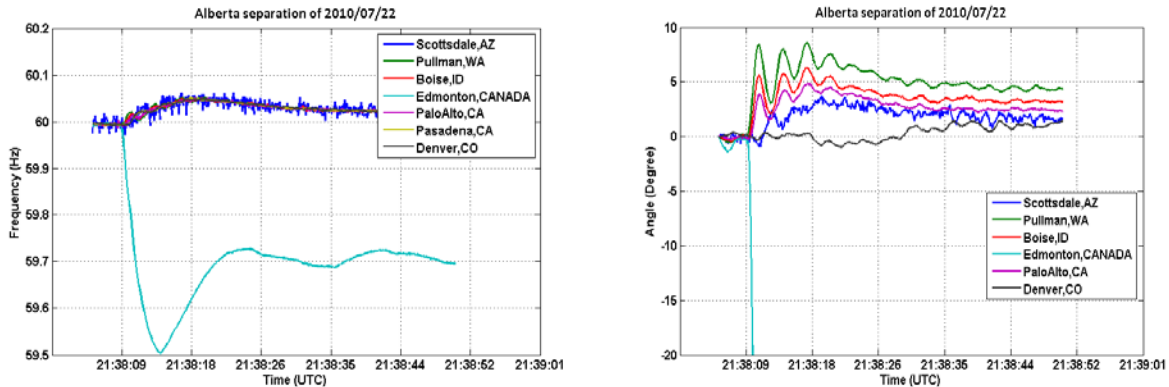
Fig. 7-34. 0.3 Hz mode shape of Alberta separation of 2010/06/01

- **Case 2: Alberta Separation on July 22, 2010**

There was another similar disturbance captured on July 22, 2010, which also disconnected Alberta from the WECC system. The frequency excursion and relative angle

oscillation is shown in Fig. 7-35. Taking all FDR data (except data from the Alberta unit) for Matrix Pencil analysis, the results are listed in Table 7-16.

As shown in Table 7-16, the only dominate mode appeared near 0.3Hz. The mode shape for the 0.3Hz mode is shown in Fig. 7-36, in which the northern (WA,ID) and CA area oscillated together.



(c)

Fig. 7-35. Frequency excursion and Relative angle of Alberta separation of 2010/07/22

Table 7-16 Modal analysis results of Alberta separation of 2010/07/22

Modes (Hz)		Pullman	Boise	Palo Alto
0.3	f	<u>0.322</u>	<u>0.322</u>	<u>0.320</u>
	α	7.34	7.10	8.75

Note: f means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red text indicates the dominant mode.

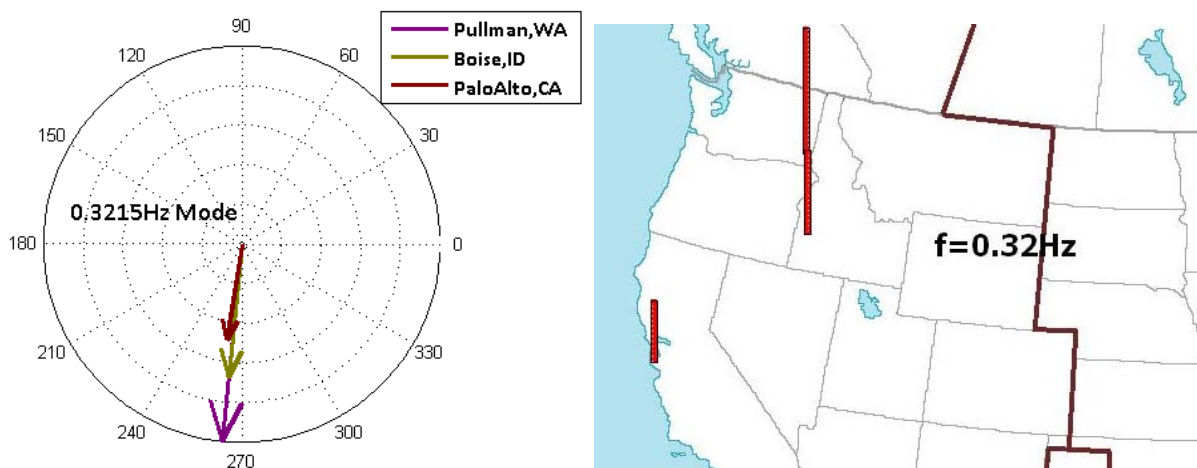


Fig. 7-36. 0.3Hz mode shape of Alberta separation of 2010/07/23

- **Case 3: Alberta Separation on Sept 8, 2010**

One more line trip occurred on Sept 8, 2010, which caused the Alberta separation. The frequency excursion and relative angle oscillation is shown in Fig. 7-37. Taking all FDR data (except the Alberta unit) for Matrix Pencil analysis, the analysis results are listed in Table 7-17.

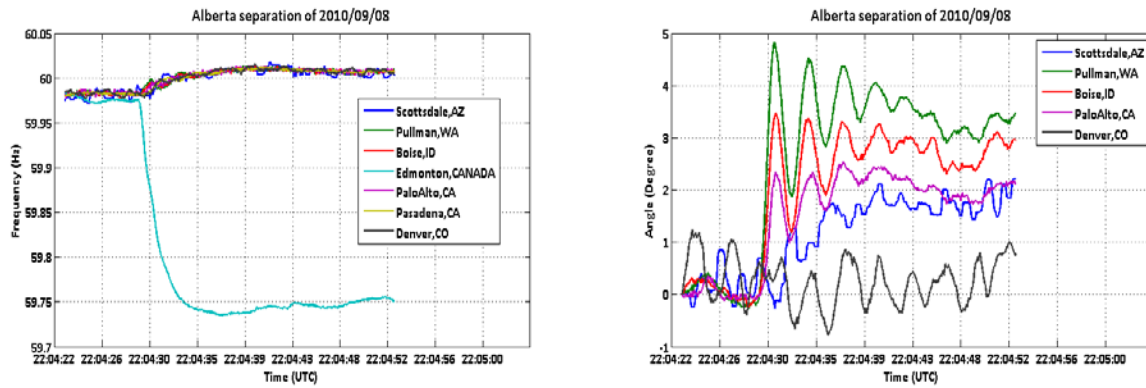


Fig. 7-37. Frequency excursion and Relative oscillation angle of Alberta separation of 2010/09/08

Table 7-17 Modal analysis results of Alberta separation of 2010/09/08

Modes (Hz)		Pullman	Boise	Palo Alto
0.3	f	<u>0.326</u>	<u>0.319</u>	<u>0.330</u>
	α	8.54	8.53	7.70

Note: f means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red text indicates the dominant mode.

As shown in Table 7-17, the only dominate mode appeared near 0.3Hz. The mode shape for the 0.3Hz mode is shown in Fig. 7-38. The same mode shape is observed as in previous case, in which the northern (WA, ID) and central CA area oscillated together.

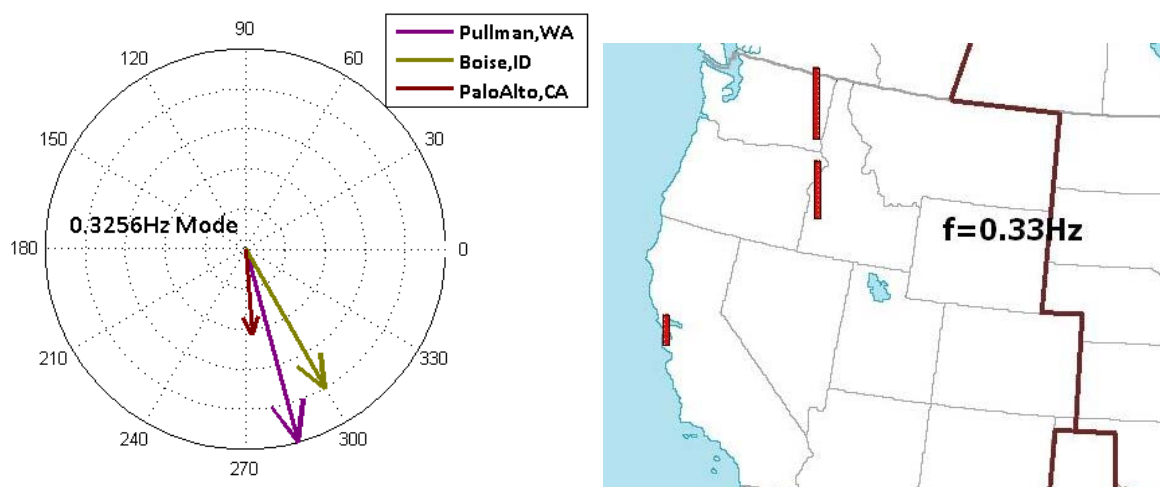


Fig. 7-38. 0.3Hz mode shape of Alberta separation of 2010/09/08

- **Case 4: Alberta Separation on June 8, 2011**

One more line trip occurred on June 8, 2011, which caused Alberta separation. The frequency excursion and relative angle oscillation is shown in Fig. 7-39. Taking all FDR data (except the Alberta unit) for Matrix Pencil analysis, the analysis results are listed in Table 7-17. With an increasing FDR deployment in WECC, there are more FDRs available for analysis in this case.

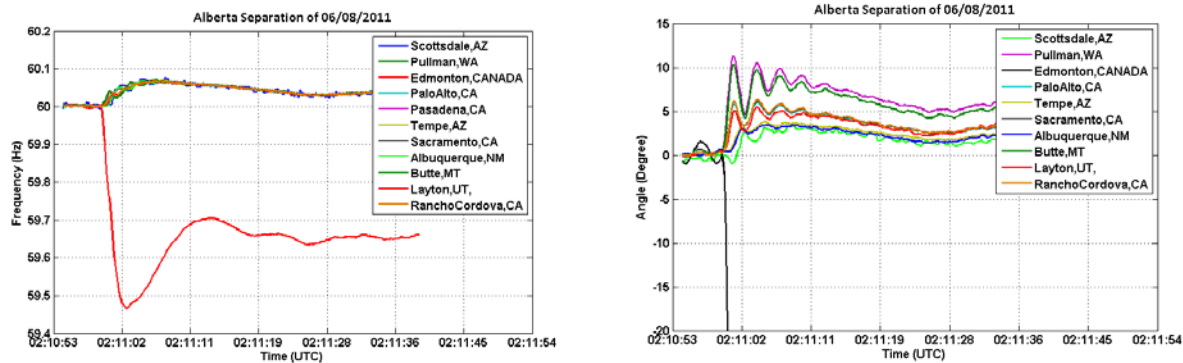


Fig. 7-39. Frequency excursion and Relative oscillation angle of Alberta separation of 06/08/2011

Table 7-18 Modal analysis results of Alberta separation of 06/08/2011

Modes (Hz)		Pullman	Palo Alto	Tempe	Sacramento	Albuquerque	Butte	Layton	Rancho Cordova
0.3	f	<u>0.347</u>	<u>0.346</u>	<u>0.341</u>	<u>0.300</u>	<u>0.327</u>	<u>0.352</u>	<u>0.348</u>	<u>0.348</u>
	α	11.44	9.76	14.15	39.11	15.84	12.93	14.04	10.88

Note: f means damping frequency in Hz; α means damping ratio in %; '-' means this mode is not available or with small oscillation magnitudes. Red text indicates the dominant mode.

As shown in Table 7-18, the only dominate mode appeared near 0.3Hz. The mode shape for the 0.3Hz mode is shown in Fig. 7-40. It turns out that the northern and CA areas oscillated against southeastern area at the 0.30Hz mode. The FDRs in northern areas (WA and MT) exhibited the most significant oscillation magnitude.

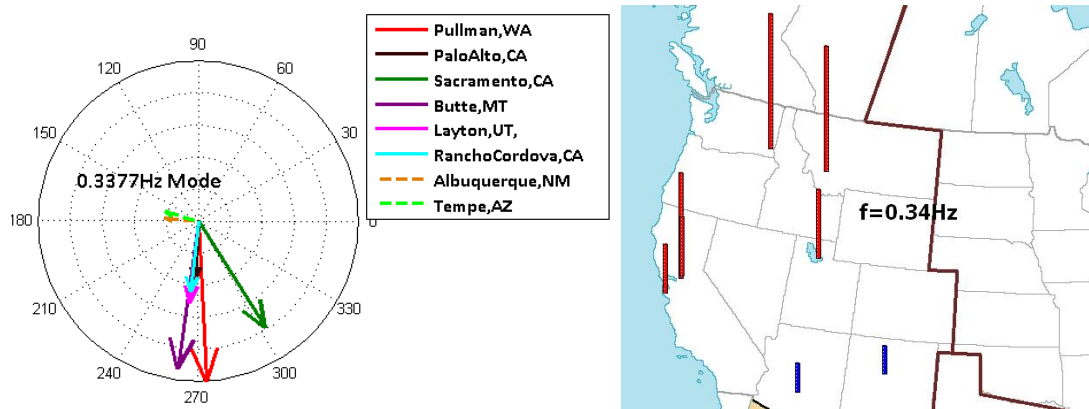


Fig. 7-40. 0.3Hz mode shape of Alberta separation of 2011/06/08

7.3.3.3 Summary

Some conclusions can be drawn from the analysis.

1. In Type-I line trip events, four modes may appear in these oscillation cases triggered by line trips with Alberta connected: $\sim 0.2\text{Hz}$, $0.3\text{-}0.4\text{Hz}$, 0.6 , and $0.7\text{Hz-}0.8\text{Hz}$. Not all these modes appear simultaneously for every case.

2. For Type-I line trip events; the most common dominant mode is 0.4Hz mode. The Alberta still exhibits the 0.2 Hz mode with dominant mode in most cases. And the 0.6 and $0.7\text{-}0.8\text{ Hz}$ modes are not as common as the other two modes; it may appear in some FDR units in some oscillation cases.

3. For the 0.4Hz mode, the most common mode shape is that the Alberta oscillates against the northern and CA areas, which is consistent with the mode shapes observed in oscillations triggered by generation trips (Fig. 7-22 in Section 7.3.2).

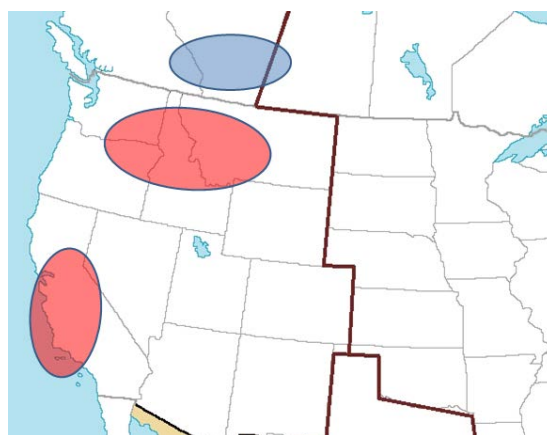


Fig. 7-41. Common mode shape for 0.4Hz mode

4. For Type-II line trips with Alberta separated from WECC system, the Alberta-associated mode may disappear or attenuate, then the inter-area mode shifts to near 0.3Hz, in which the most common mode shape is the northern and CA areas oscillate together, or oscillate against the southeastern areas (AZ,NM) when the data in that areas are available (Fig. 7-42).

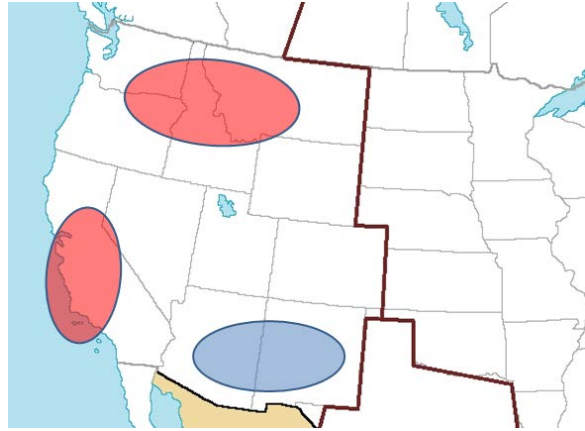


Fig. 7-42. Common mode shape for 0.3Hz mode in Line trip with Alberta disconnected

7.4. Conclusion

Based on the wide area measurements taken in the FNET, the oscillations incited by different types of disturbances are analyzed using the Matrix Pencil tool in the WECC system. Various oscillation information is extracted, such as oscillation modes, damping factor, and oscillation mode shapes. The modal analysis of synchrophasor measurements provides wide-area geographic visibility of power system oscillations in WECC. The following conclusions can be drawn from the case studies:

1) Among oscillations triggered by generation trips, 4 modes may appear: $\sim 0.2\text{Hz}$, 0.35-0.4Hz, ~ 0.6 and $\sim 0.7\text{Hz}$ modes. Usually the $\sim 0.2\text{Hz}$ and 0.35-0.4Hz modes are two most common dominant modes. For the 0.2Hz mode, the Alberta unit shows largest oscillation magnitude compared with others. The mode frequency spans from 0.22Hz to 0.28Hz. The most common mode shape for 0.2Hz mode is the Alberta, Northern and CA areas oscillate against the southern areas.

2) Among oscillations triggered by Type-I line trips (with Alberta area connected), similar oscillation patterns are observed to oscillations triggered by generation trips. The 0.2Hz and 0.35-0.4Hz modes are still frequently incited during most cases. The 0.4Hz is the most common

dominant mode among all the active FDRs, and the most common mode shape for this mode is that the Alberta area oscillates against the northern and CA areas.

3) Among oscillations triggered by Type-II line trips (with Alberta area separated), the dominant mode shifts to near 0.3Hz. For this mode, the northern and CA areas oscillate together, or oscillate against the southeastern area (AZ,NM) when the data in that areas are available. And usually the unit in Pullman, WA has most significant oscillation strength for this mode.

Chapter 8. Conclusion & Future work

8.1. Conclusion

The dissertation covers works from situational awareness application development, system design to power system disturbance analysis. Especially this dissertation lays the groundwork for future angle-based situational awareness applications.

At the first step, the dissertation proposes the event location method with the FNET phasor angle measurement instead of traditional frequency measurement. Two major methods are proposed: TDOA-based event location triangulation that explores the electromechanical wave propagation information embedded within angle measurement, and oscillation-based event location estimation that explore the angle oscillations associated with disturbance transient period. A set of supplementary approaches are designed to enhance the estimation accuracy, e.g. angle data referencing, event time refinement, multiple threshold settings, etc. The offline testing with historical event cases proves the effectiveness of the angle-based method in locating the power system disturbances. Nearly 51% of the estimated locations are within 100 miles radius from the actual location. And it turns out that the angle data serve the purpose better than the frequency data.

Secondly, the viability of FNET angle measurement in serving system visualization is investigated. A real-time angle visualization framework is proposed and implemented in this work. This framework interprets real-time FNET angle measurement and provides the power system awareness in a graphic way. The framework covers two basic functions: real-time angle contour map display, recording and animation playback for recent time window. These functions are designed to be accessible through FNET web services.

After that, the dissertation touches on the FNET system architecture and function additions, where the FNET power system event monitoring and automatic event reporting system is constructed and enhanced with NERC Frequency Response Initiative (FRI) tasks included. The system includes multi-thread event trigger mechanism, flexible event recording design, on-line event analysis modules (e.g. location module, FRC calculation module, plotting modules), on-time event alerting modules, etc.

After those situational awareness system development works presented above, some power system analysis works are touched upon based on the real wide-area measurements taken in the FNET system. Firstly, the frequency disturbance statistics in NA power grid are

analyzed from 2008 to Sept, 2011. The comparisons are performed between EI and WECC system on the generation trip and load shedding disturbances. Furthermore, with FDR deployment in some other worldwide countries, e.g. Europe, some typical frequency responses are observed, and some disturbance statistics are also analyzed and compared with NA power grid.

Secondly, different types of major disturbances in EI and WECC from 2010 to 2011 are investigated. The disturbances covers the HVDC line trips, large generation drop, large load shedding, power system islanding and large system blackout, etc. All the local frequency, phase angle and voltage measurement from FNET system are considered. The dynamic system responses to different disturbances are reflected in the distribution level measurement.

Lastly the dissertation proceeds to the oscillation modal analysis. An extensive modal analysis with Matrix Pencil tool is performed on different types of disturbances in WECC. Three basic types of disturbances are considered: generation trip, line trip with Alberta connected, line trip with Alberta islanded. The typical oscillation mode shapes associated with different disturbances in WECC are listed through the analysis.

8.2. Future work

The work reported in this dissertation can be the foundation for future researches associated with wide area monitoring application developments. The followings could be the possible future works:

For the oscillation-based event location methods, it is necessary to evaluate its effectiveness in WECC system, since the WECC system has different oscillation characteristic associated with frequency disturbances.

For the FNET event monitoring and reporting framework, more functions can be added to improve the system performance, e.g. additions of Alarm Layers in Reporting System, refined FRC analysis, improved oscillation monitoring capability, etc. And with the increasing of FDR deployment in the European power grid, more situational awareness applications can also be applied, such as event location estimation.

For the real-time angle visualization framework, currently the real-time angle contour map display is accessible through FNET website. In the future, the VTK-based real-time visualization module can be developed to work as an individual client-side program, retrieving FNET wide-

area angle measurement from FNET server system through authenticated connection. Such client-side software design may require a sophisticated design of FNET web server.

And currently the real-time angle contour map only covers the EI system; it can expand to WECC system with sufficient FDR deployment in WECC.

For statistical disturbance analysis work, with further accumulation of the FNET event database over other worldwide power grid, e.g. Korean, China, a more comprehensive system profile regarding disturbance statistics in these power grids can be drawn and compared with North America power grid.

For the oscillation modal analysis in WECC, with increased FDR deployment across WECC, the modal analysis can be performed on future oscillation disturbances to provide a more comprehensive view of the inter-area mode distribution in WECC.

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Vita

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