# Power Systems Frequency Dynamic Monitoring System Design and Applications

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ABSTRACT

Recent large-scale blackouts revealed that power systems around the world are far from the stability and reliability requirement as they suppose to be. The post-event analysis clarifies that one major reason of the interconnection blackout is lack of wide area information. Frequency dynamics is one of the most important parameters of an electrical power system. In order to understand power system dynamics effectively, accurately measured wide-area frequency is needed. The idea of building an Internet based real-time GPS synchronized wide area Frequency Monitoring Network (FNET) was proposed to provide the imperative dynamic information for the large-scale power grids and the implementation of FNET has made the synchronized observations of the entire US power network possible for the first time. The FNET system consists of Frequency Disturbance Recorders (FDR), which work as the sensor devices to measure the real-time frequency at 110V single-phase power outlets, and an Information Management System (IMS) to work as a central server to process the frequency data. The device comparison between FDR and commercial PMU (Phasor Measurement Unit) demonstrate the advantage of FNET. The web visualization tools make the frequency data available for the authorized users to browse through Internet.

The research work addresses some preliminary observations and analyses with the field-measured frequency information from FNET. The original algorithms based on the frequency response characteristic are designed to process event detection, localization and unbalanced power estimation during frequency disturbances. The analysis of historical cases illustrate that these algorithms can be employed in real-time level to provide early alarm of abnormal frequency change to the system operator. The further application is to develop an adaptive under frequency load shedding scheme with the processed information feed in to prevent further frequency decline in power systems after disturbances causing dangerous imbalance between the load and generation.

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**To My Parents and My Wife Huijuan**

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# List of Acronym and Symbols

ACE: Area Control Error
ADC: Analog to digital convector
AGC: Automatic Generation Control
API: Application Program Interface
ECAR: East Central Area Reliability Coordination Agreement
EMS: Energy Management System
EPRI: Electric Power Research Institute
ERCOT: Electric Reliability Council of Texas
EST: Eastern Standard Time
EUS: Eastern US Interconnection
FACTS: Flexible AC Transmission System
FDR: Frequency Disturbance Recorder
FFT: Fast Fourier Transforms
FNET: Frequency Monitoring Network
FRCC: Florida Reliability Coordinating Council
GPS: Global Position System
GUI: Graphical User Interface
HTML: Hypertext Markup Language
IMS: Information Management System
IP: Internet Protocol
ISO: Independent System Operator
ISO: International Standard Organization
IT: Information Technology
LAN: Local Area Network
MAAC: Mid-Atlantic Area Council
MAIN: Mid-America Interconnected Network
MRO: Midwest Reliability Organization
NERC: North American Electrical Reliability Council
NPCC: Northeast Power Coordinating Council
ODBC: Open Database Connectivity
PMU: Phasor Measurement Unit
PSS/E: Power System Simulator for Engineering
SQL: Structured Query Language
SCADA: Supervisory Control and Data Acquisition
SERC: Southeastern Electric Reliability Council
SPP: Southwest Power Pool
STD: Standard Deviation
TCP: Transport Control Protocol
TDOA: Time Difference of Arrival
UDP: User Datagram Protocol
UFLS: Under Frequency Load Shedding
WAMS: Wide Area Measurement System
WECC: Western Electricity Coordinating Council

# Chapter 1 Introduction

The electric power generation, transmission, and distribution systems are extremely important to our modern society. It is a very critical issue for power system engineers to keep the power grid stable and reliable. Large power systems are interconnected to enforce reliability. Electric power system receives many benefits by operating with such interconnection. Individual system reliability could be enforced because of improved frequency response to contingencies such as loss of load or generation. Frequency changes for a given loss of load or generation are smaller for a large, interconnected system than the corresponding frequency changes for the isolated control areas.

The electric power system is a complex interconnected system. The loads and the network topology of the power system change randomly in real time, and the generation must change instantaneously in order to satisfy the demand. Any slight mismatch will give rise to instantaneous frequency fluctuation in different areas of the network. Electromechanical oscillations occur when the system responds to large disturbances such as those triggered by faults and component failures. Using traditional off-line simulation studies is impossible to model the complexity, especially the constant changing operation conditions of large power systems.

## 1.1 Blackouts and Power System Disturbance Analysis

Power systems are supposed to operate in a way that will not cause large area power lose and can stand when some generators lost in the grid. However, so many large-scale blackouts happened in recent years show that power system could become vulnerable [1] in the face of possible system abnormalities such as control, protection or communication system failures, disturbances and human operation errors. A big issue of blackout is information is lack during the event period. A lack in awareness of the power system status caused the recent 2003 summer blackout in the US [2][3]. The blackout started with some uncritical generator outages in northern Ohio, leaving the system with n-1 contingency reserves. An initial key incident, the loss of the Stuart-Atlanta 345kV transmission line due to a flashover, also did not look serious in terms of system stability. Together with operator error, however, it led to a situation where the state estimator program at one of the EMS control centers could not assess the system condition. Being a prerequisite for contingency analysis, these programs could not be run either. They would normally calculate the affects of simulated failures on the system and alert operators to critical conditions. In addition, computer failures at another EMS control center deprived the operators of the alarm functions. Unaware of the function loss and consequentially relying on outdated information for one hour, operators could not see that the power system was in the initial stages of degradation.

The blackout in Italy was also caused by a lack of power system information [3][4]. September 28, 2003 was a Sunday and the blackout sequence started at 3 am. Making use of cost advantages, Italy was importing about 24 per cent of its then relatively low total demand via France, Switzerland, Austria and Slovenia. The Swiss transmission grid was heavily loaded near its n-1 limit. A flashover caused one of the main 380kV lines across the Alps to trip. An attempt to re-close the line failed, as the phase angle difference was too high due to the high power flows. This and insufficient load shedding in Italy caused overloading of the other main 380kV line, which eventually sagged and also tripped due to a flashover. From this point onwards, a cascade failure was inevitable. The other lines to Italy were overloaded, it lost synchronization with the rest of Europe, the remaining lines tripped and Italy was isolated. There was a large generation deficit within the islanded Italian system and despite further load shedding the system collapsed completely two minutes after isolation.

One alternative to prevent such kind of blackout is to run power systems with more reserves, while this method is expensive and hardly acceptable in today's deregulated markets with competition and pressure on costs. Another alternative is to improve the real-time wide area information that is available to operators. Wide area monitoring is a viable alternative as it not only increases system security, but also allows the power system to run at its pre-defined security margin, thus saving costs. These blackouts demonstrate that wide area, comprehensive and real time information exchange is becoming a critical factor for the reliability and stability of the future power system.

## 1.2 Wide Area Measurement System and Phasor Measurement Unit

Real time data can be highly valuable information source for automatic control to maintain system stability; it can also be used as a guide to immediate operating decisions in support of system recovery and for extensive analysis [5][6]. The real time data applications [7] range from very rapid control function to the very slow functions such as expansion planning. With high-speed real time measurement, proper protection and control actions could be taken to ensure the reliability of power system when event occurs.

Information and measurement systems are evolving rapidly within the electric power industry. With new classes of instruments becoming available, new operating and regulatory environments, and new computing and communications capabilities, the time is right for industry stakeholders to make better use of measurements and information to improve system performance.

The phasor measurement unit (PMU) [8] is a device capable of measuring the synchronized voltage and current phasor in a power system. Synchronicity among phasor measurement units is achieved by same-time sampling of voltage and current waveforms using a common synchronizing signal from the global positioning satellite (GPS). The ability to calculate synchronized phasors makes the PMU one of the most important measuring devices in the future of power system monitoring and control.

Phasor measurement algorithms were developed in the late 1980’s to calculate phase angle from voltage measurements. The world’s first prototype PMU was developed at Virginia Tech [8]. The PMU was soon used widely for a variety of applications such as monitoring of the bulk transmission systems as well as state estimation and stability studies [9][10]. Most notably, projects including those by EPRI [9] and DOE wide area measurement system (WAMS) [10], and recently the Eastern Interconnection Phasor Project (EIPP) [11] were launched using phasor measurement techniques for power system measurement and monitoring.

Wide area measurement system (WAMS) is to place sensors/recorders across a wide area to record power system's states, e.g. voltage, current, phasor angle, frequency, power, etc. To obtain meaningful measurements, the device/sensor has to be accurate enough to extract the desired information from measured signal(s). In most cases, only the time information is needed for WAMS and position data is required only once during initialization, since we are most concerned about having synchronized-time measurement among different devices. Several event recordings from WAMS were reported in [12-22]. Nowadays, there are lots of commercial PMU from different manufactories, such as ABB, Arbiter, Macrodyne, and SEL, available for the different applications all around the world.

## 1.3 Power System Frequency Response Research

System frequency is normally the same at all points of the power network at steady state. Networks at all voltage levels share a characteristic: from generation all the way through transmission, distribution, and consumption nodes. However, when a significant disturbance occurs, the frequency varies in time and space, and in many ways, it exhibits the characteristics of electromechanical wave propagation phenomena. Although static power frequencies are currently being measured all over the system for various applications, they have limited dynamic accuracy and are lack of common time, and such information is not suitable for large-scale observations [23].

Frequency Response is the characteristic displayed by load and generation within control areas, and therefore an interconnection, in response to a significant change in load-resource balance [24]. Because the loss of a large generator is much more likely than a sudden loss of load, frequency response is typically discussed in the context of a loss of a large generator. The energy used (by loads) must be equal to the energy provided (by generators) to maintain a steady frequency. Frequency is essentially the same throughout an Interconnection and is easy to measure. Abnormal frequencies can damage power system equipment, especially steam turbines.

It is well known that all generators have some type of governor. There are a couple added features to a governor. When a generator synchronizes to the Interconnection, it couples itself to hundreds of other machines rotating at the same electrical speed. Because all generators have this “droop” feature added to their governor, they will all respond in proportion to their size whenever there is a disturbance or load-resource mismatch [24].

In the interconnected power systems [25][26], each sub system maintains a balance between generation and load under normal conditions. Automatic Generation Control (AGC) [26] provides the fine-tuning for system frequency. Each control area responds to a frequency deviation according to the natural response of its turbine governors and its load. This balance will be lost if the generation trip occurs or load is increased. When a control area has lost generation or load, the rest of the Interconnection provides immediate support for the frequency through governor action. If control areas set their AGC Bias close to their natural Frequency Response, only the contingent control area will see a change in its Area Control Error (ACE). When some areas are unable to maintain generation/demand balance, other areas will provide sustained assistance according to bias characteristics.

## 1.4 Frequency Monitoring Network (FNET)

Frequency information can be useful in many areas of power system analysis, operation, and control. Typically, only static frequency measurements [30][31] are widely available. This is because most of frequency measurement devices assume a single system frequency, and they use long periods of data averaging in order to achieve good estimation accuracy. This is not a problem when the system is in its steady state. However, the most valuable frequency data are those obtained during disturbances, when the system frequency is time varying, and when frequencies could be very different in different parts of the system. Accurate dynamic wide-area measured frequency is highly desirable [32], especially as blackout events are becoming increasingly severe in power systems around the world [2-4]. Power engineers have worked for decades to develop measurement tools for observing a power system's dynamics. The synchronized Phasor Measurement Unit (PMU) was developed and later commercialized in the late 1980's. Since then, a number of applications have been proposed that require wide-area measurement systems. The results of all earlier efforts clearly point to the need for much wider measurement coverage.

PMU is used to build a wide area measurement system, while because of the cost-efficient issue, permission from utility, information exchange between different companies and so many other issues, we still do not have a national wide monitoring system to keep an eye on power system. Due to the cost of high voltage substation installation and other complications, PMU coverage is growing at a speed that is much slower than expected in US. Power system deregulation [24] results in information consolidation and open access, and pushes for more extensive internal and external utility information exchange, integration, and dissemination. Inter-company communication and integration of data from various control centers, power plants, and substations have become necessary.

The idea is to use some cost-efficient monitors as frequency sensor, which connects to the system at distribution level to avoid the issue of permission, and then send back the local frequency value of different locations thru the Internet to the central server. The objective is to create an extremely low cost and quickly deployable wide-area GPS synchronized frequency measurement system with high dynamic accuracy, and that requires a minimal installation cost. All these features are possible in FNET because the power system frequency can be accurately measured and GPS synchronized at 110V distribution voltage level of a typical office outlet [34].

When a significant disturbance occurs in a power system, the frequency varies in time and space [35]. The FNET system is used to monitor the changing frequency in continuous time and in different locations. Dynamic measurement accuracy is critical. The frequency estimation algorithms developed for FNET have virtually zero algorithm error in the 52-70Hz range. During the past three years, the first generation of the FNET system was completed.

The FNET implementation includes: the development of highly accurate algorithms and techniques that are immune to various noises at the distribution level; the design and development of sensor hardware; the development of an Internet based information management system; the development of real-time and offline post processing algorithms; the study of advanced data aggregation methods from hundreds of other possibly heterogeneous sensors.

## 1.5 Under Frequency Load Shedding (UFLS)

Power systems in running conditions could suffer from different kinds of contingencies. Such emergency conditions could be loss of generation, under frequency, low voltage or oscillations. Due to the system complexity and corresponding static and dynamic problems involved, they are difficult to operate and control. Frequency instability scenario can be initiated by a large mismatch between generation and load [36][37]. Such a scenario can result in a cascaded loss of generation through under-or over-frequency related operation that would eventually lead to a blackout if the total spinning reserve can not compensate for the generation loss sufficiently[38][39][42]. Under frequency load shedding scheme [40] is commonly implemented in isolated and large interconnected system as an emergency measure in case of falling frequency conditions or loss of power generation. Traditionally, the load shedding scheme was evaluated and set using simulation [41] based on the assumption of constant deceleration, constant voltage, constant load and constant generator power. The scheme was adequate for simple and special cases. To serve as emergency frequency drop protection, load shedding scheme is designed and activated at different frequency levels to shed pre-selected and fixed amount of loads. However, due to the power system complexity, different system running conditions and dynamic performance variation, the load shedding amount is difficult to predict and may not match the generation unbalance. The frequency could continue to drop due to under load shedding, or the frequency would jump up due to over load shedding.

The main goal of UFLS is to gradually shed portions of the load when the frequency of this relay reaches values lower than allowed (e.g. if $f < f_1 = 59.5Hz$, after time delay $\Delta t_1$ = 0.1s, shed 0.1 p.u. load of the relative bus). Time delays per step are introduced to ride out short-time transient frequency excursions. Every power system has its own UFLS plan, which is coordinated with the plans of neighboring power systems. There have been many publications on utility implementation of UFLS.

The traditional load shedding relays shed load in several steps with the preset tripping frequency and pre-designated feeders derived from assumed system conditions and load distributions. Therefore, it will inevitably result in either over or under shed, as it cannot adapt to the continuous changes in system conditions. Load shedding algorithms are designed off-line from operational experiences and simulations. The traditional scheme is a one-size-fits-all compromise of different operation scenarios. However, when system operation status is changed, the load-shedding scheme cannot be easily modified to adapt to new system conditions. The other drawbacks are that each local protection device is not considering a system view and are, therefore, not able to take optimized and coordinated actions. The results of the early efforts point to the need of fast and accurate load shedding strategy. In recent years, technology advances in networking and communication as well as in power system design have opened the door for fast and accurate load shedding system design. With wide-area FNET information, especially with more accurate generation trip amount and location estimation, advanced load shedding schemes can be developed.

## 1.6 Organization of the Dissertation

This dissertation addresses two main issues for the power system frequency monitoring and analysis: how to get the frequency information and how to use the frequency information. The major objectives of the dissertation are to develop and implement the frequency monitoring network; systematically analyze field-measured frequency information; detect the disturbances in power grid and estimate the location of the disturbance; develop the adaptive UFLS with analyzed frequency information as input.

In Chapter 2, the idea and the architecture of FNET system is introduced in detail, and it describes the implementation of FDR, IMS. Chapter 3 reports a comparison of FDR and commercial PMU. Chapter 4 addresses the static and dynamic analysis with the field-measured frequency from FNET system. Chapter 5 represents the disturbance analysis based on the wide area frequency information. Chapter 6 pictures the adaptive UFLS scheme with real-time frequency as input information. Chapter 7 concludes.

# Chapter 2 Frequency Monitoring Network Architecture and Implementation

Frequency is an important parameter in power systems, and accurate real-time measured frequency is highly desirable in wide-area to understand the dynamics of power systems. The concept of building an Internet based real-time GPS synchronized wide-area Frequency Monitoring Network (FNET) has been implemented and realized. The FNET system consists of an array of Frequency Disturbance Recorders (FDR) and an Information Management Server (IMS). The FNET system has made observations of the country's entire power network possible for the first time. This chapter discusses the architecture of FNET and describes how to implement each component of FNET.

## 2.1 The Idea of the Frequency Monitoring Network

In order to meet the requirement of frequency measurement, the Frequency Monitoring Network (FNET) was first proposed in the paper "Internet Based Frequency Monitoring Network" [34], which presents the idea, designs the system architecture and describes the main parts of the system. The motivation for FNET was to build a system, which could monitor the power system frequency in real-time and could also analyze the frequency data to get the system status information for system control and operation.

With the integrated GPS clock, FDR units can measure the local system frequency in different dispersed locations synchronously. FNET provides a common time stamp, which helps to reconstruct what happened after major events. One of the delays in determining the causes of the 2003 blackout was the use of different timing references by the companies involved.

The wide-area, synchronized measurement system is based on the concept that in steady state the system frequency remains constant regardless of voltage level. However, when a significant disturbance occurs in the power system, the frequency varies in time and space. The FNET system can be used to monitor the changing frequency in continuous time and in different locations. With the effort of the research team on this project, the FNET system started operation in summer of 2004, and FDR units have been installed in 15 locations as of July 2005. The FNET system has made observations of the country's entire power network possible for the first time. A crucial innovation is to take measurements at the 110 V level of the power grid, avoiding major obstacles in high voltage substation installations, thus, significantly reducing overall cost, and enabling measurements to be made at a large number of locations.

## 2.2 Architecture of Frequency Monitoring Network

The FNET system is a wide-area sensor network consisting of high accurate frequency disturbance recorders and a central processing server. Figure 2.1 shows the framework of the FNET system. The FNET system consists of two major components: a) Frequency Disturbance Recorders (FDR), which work as sensors to perform local frequency data measurements and to send data to the server through the Internet; b) The Information Management Server (IMS), which includes data collection, storage, communication service, database operation, and web service. The Internet provides the wide area communication network between the FDR units and IMS server.

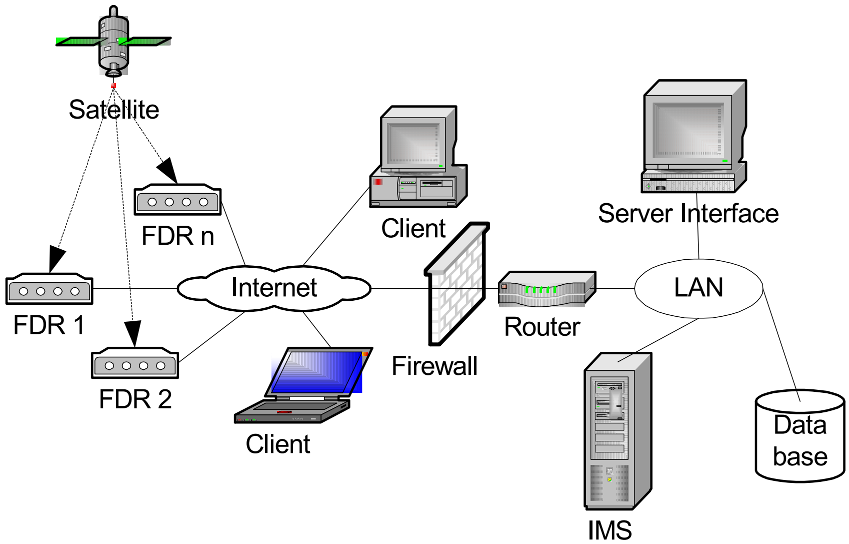



Figure 2.1 Frequency Monitoring Network Architecture

The FDR is the data acquisition device of the FNET. Although only 15 units are installed at this moment, there will be a large number of FDR units geographically dispersed across the United States to gather frequency data from different locations in the US power grid. Internet is used to transmit the information to a central server, currently located at Virginia Tech.

The IMS server plays a vital role in the FNET system. It was developed base on the multi-tier client/server architecture that models, coordinates, and integrates the frequency acquisition, processing and display functions. IMS server performs four roles: Internet client service, FDR communication function, Database operation and Web services. The frequency data is transmitted to the IMS server through WAN (Wide Area Network) in real time. IMS Server receives and processes the data, logs the data to the database server and publishes the data to the web. The current GUI (Graphical User Interface) is built as a local monitoring server, which integrates the frequency display, monitoring and storage. At the same time, our server provide web service to publish and display the frequency in real-time. The designed future function includes historical data retrieval, automatic analysis and historical data retrieval into a common easily accessible user interface. The IMS Server is written entirely in C++ and the web service is written in PHP and Java.

Communication is based on TCP/IP protocol. The server open the relative ports for clients, when the data coming, the socket process receives and then put it into database. Communications protocols are methods for transmitting data between networked computers. The most popular low-level protocol in use on the Internet is IP (the Internet Protocol). Higher-level transport protocols run on top of IP to provide added functionality. The two integral networking protocols in IP-based networks such as the Internet are the Transmission Control Protocol and User Datagram Protocol. TCP is the more popular of the two. In the FENT project, TCP is selected to work as communication protocol to guarantee the integrality of the frequency data.

## 2.3 Frequency Disturbance Recorder Architecture

A FDR unit consists of a voltage transducer, a low pass filter, an analog to digital (A/D) converter, a GPS receiver, a microprocessor, and the network communication modules as shown in Figure 2.2. The voltage transducer takes an analog voltage signal from an 110V wall outlet and converts it to acceptable A/D levels, the low pass filter eliminates the high frequency components, and the A/D converter transforms the analog signal into digital data. A microprocessor is used to generate the sampling pulses synchronized to the 1pps from the GPS receiver integrated into the FDR. The phase angle, frequency, and rate of change of frequency are computed using phasor techniques developed specifically for single phase measurements [42]. The computed values are time stamped, and transferred to the IMS via the Internet. Figure 2.3 shows an FDR unit.

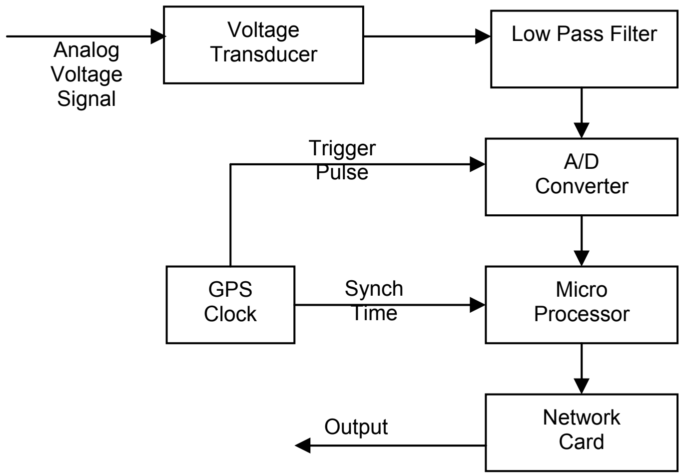



Figure 2.2 Frequency Disturbance Recorder Structure


Figure 2.3 Outlook of Frequency Disturbance Recorder (FDR)

In order to meet the most important requirement of a wide area frequency measurement, a GPS clock is integrated into the FDR unit to generate the sampling pulses that trigger the A/D converter and ensure the synchronized data acquisition. At the same time, the GPS clock provides a timestamp for each A/D conversion. Thus, data sampling is synchronized to a common time reference.

Static frequency computations are usually done on voltage waveforms due to their relatively unchanging nature during normal operating conditions. The FDR unit makes frequency calculations using algorithms of phasor analysis and signal re-sampling techniques. The complexity of the calculations is minimized to allow the microprocessor time to complete its other tasks and prevent data overflow. The current version of FDR has a sampling rate of 1440Hz and the resulting frequency accuracy is ±0.0005Hz or better. Based on earlier studies, this accuracy meets the requirements for monitoring and capturing both slow and fast frequency variations. The FDR is according to the IEEE standard format for real time phasor data transmission [43].

## 2.4 Information Management System

The IMS is a vital component in the FNET system. It is based on a multi-tier client/server architecture. The IMS models, coordinates, and integrates the frequency acquisition, processing and display functions. Figure 2.4 describes the configuration of the main services and functions of the IMS server. The real-time frequency data is transmitted to the IMS server through the Internet. After receiving the data from the FDR units, the IMS server processes, time aligns, saves it in a database and provides data for the web service to display the information online. Internet provides the integrated wide area communication media between FDR and IMS server.

The IMS server has different applications. The data acquisition application communicates with remote FDR and collects the real-time information. The database focuses on providing data-related services including the real time frequency data (with GPS time-tag) storage and historical data retrieval. In the data processing tier, the on-line analytical processing services provide the capability of designing, creating and managing real time frequency database, and making them available for client applications. Historical frequency data can be retrieved from database using ASP-based web site or through Java GUI program. For important event data, compression methods are used to store the data indefinitely. To increase data transmission reliability, adaptive transmission rate and re-transmission protocols are included to improve reliability of critical data transmission. For the normal operation event data, loop storage can be used. The data will be compatible with the synchrophasor format [43].

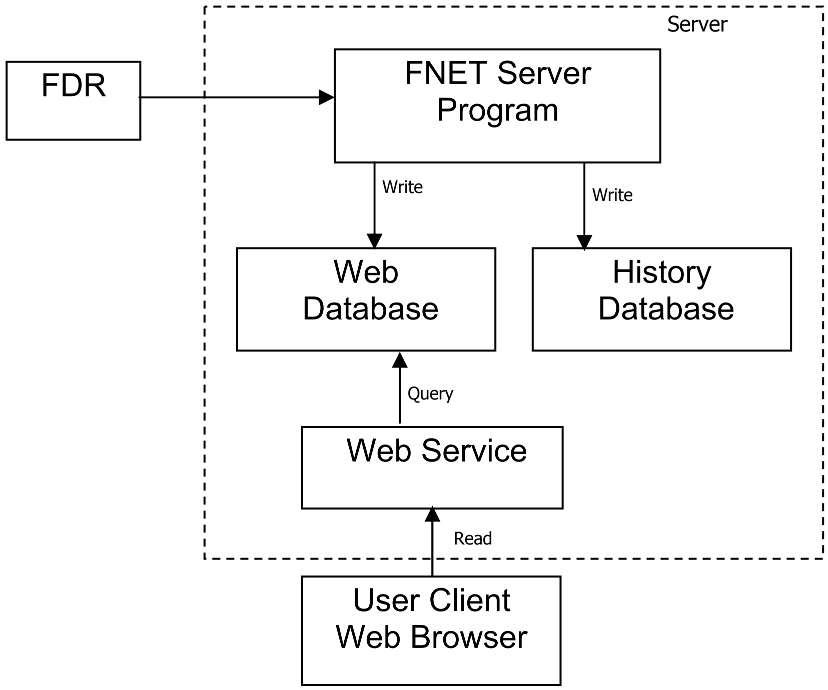



Figure 2.4 Multi-tier Information Management System Structure

The IMS is made up of three main components: the application server program, which is used to receive the frequency data from the FDR units; the database operation service, which is used to store all the data into a database and provide for frequency analysis; web service, which is used to provide an interface for the users, such as our customers and partners, who want to observe the frequency information from anywhere on the Internet. The functions and code implementation of the IMS is detailed described in Appendix A.

Multi-tier client/server architecture facilitates software development because each tier is built and run on a separate platform, thus, making it easier to organize the implementation. In addition, multi-tier architectures readily allow different tiers to be developed in different languages, such as C++ for the application tier, SQL for the database tier, and Java for the web tier. The IMS server controls data communication and database operation transactions and asynchronous queuing to ensure reliable completion of all the transactions. It also provides access to resources based on names instead of locations and, thereby, improves scalability and flexibility as system components are added or moved.

The web server provides a link to the available services to the end users via the Internet. The web server caches the Java applets, Java Internet security applets and dynamic web pages for downloading as portable programs by the user for execution. It also supports a search engine function for users to visit the historical frequency data in the database server. The users do not need to query databases, execute complex business rules, or connect to legacy applications. The web service tier will do these jobs for users transparently. There is a PHP web service run in the IIS server, and it works based on the MySQL database to provide the web service. Thus, users all around the world can access our website and observe the dynamic frequencies in a map location version of all FDR units to get the real-time frequency of the whole FNET system.

The IMS design has the following features:

- Multi-tier architecture for the IMS design provides increased performance, flexibility, maintainability, reusability and scalability for the server, while minimizing the complexity of distributed processing. These features offer powerful server architecture for the fast, reliable and large capacity data transmission and processing.

- The IMS uses the Internet as the communication infrastructure for the frequency information acquisition, transmission and distribution. The Internet provides a low investment and an easy to access platform for the data processing. The frequency data can be easily collected and transferred from the FDR units to the IMS server as well as distributed from the IMS server to the Internet users.

- The choice of the C++ language offers features such as zero client installation, on-demand access and platform independence for the Internet users. The users can access the frequency information from virtually anywhere, anytime through the Internet.

### 2.4.1 Data Processing Server Program

The FNET server program is the core part of the whole IMS. The program is used to communicate with the FDR units, receive the frequency data from FDR units, write the real-time frequency data to a historical database and web database, and to display the data in the server machine for monitoring and comparing. The server program is written in the C++ language.

The FNET server provides communication interfaces to the FDR units and backend database. The server communicates with the remote FDR units via TCP/IP and socket (end points of a two-way communication link between the two programs running on the network) communication. This communication service acts as a data transmission bridge between the IMS and FDR units. Multi-threading is used to process concurrent data streams. When a FDR unit wants to communicate with the IMS, a thread will be set up to process the data transmission from the FDR. The program also provides access to the database server, saves the data to the database and retrieves the data for display. Figure 2.5 shows the interface at the server site. It displays the FDR location information and the communication status. It also shows the real time frequency data waveform in the server interface. The server design and user manual are described in Appendix A, and it provides the definition of each class and variable. With this appendix, more real-time function can be added to enhance the performance of this program in the future, such as the event trigger and period frequency statistical report.

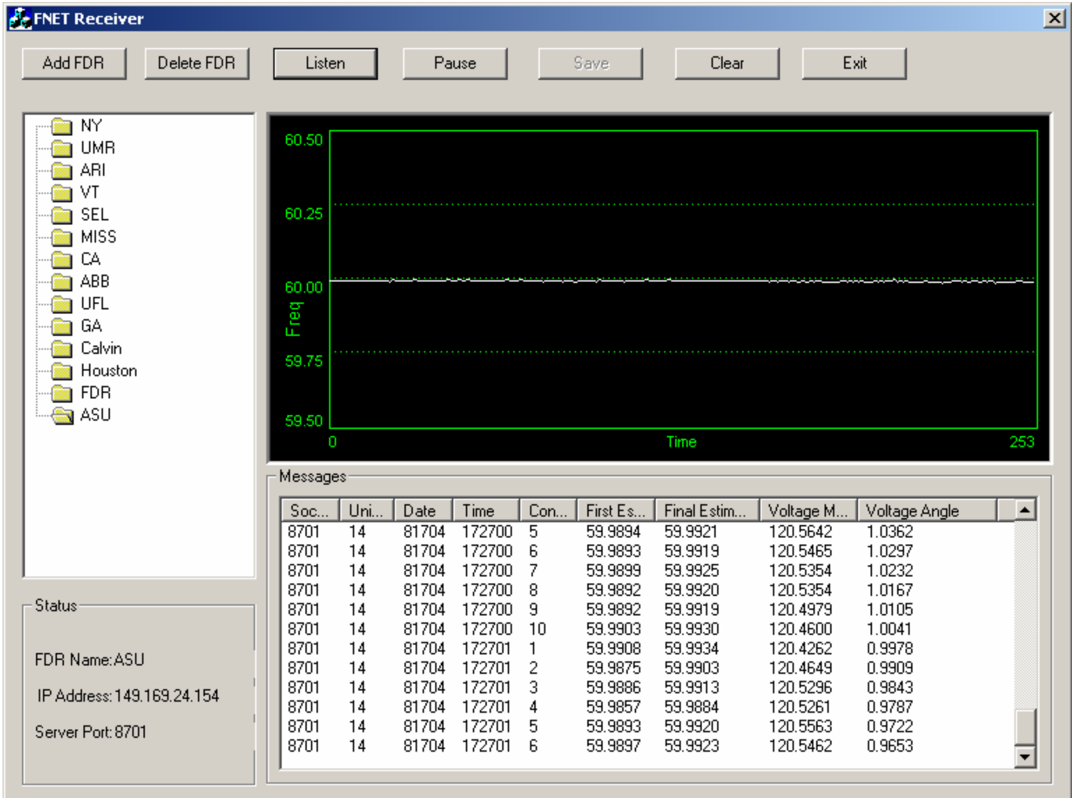



Figure 2.5 Information Management Server Program Interface

### 2.4.2 Data Communication

The server is designed for storage and displays the information from the dispersed clients, and is built on the technology of network communication and database. Communication is based on TCP/IP protocol. The server open the relative ports for clients, when the data coming, the socket process receives and then put it into database.

Networked computing systems are becoming increasingly prevalent in many areas and we believe that this growth will occur within electric utility systems as well. Technology is constantly changing, but we can make some educated guesses about what such systems will look like. First, the network systems will certainly be built from standard commercial off the shelf components. To do otherwise would be expensive both in terms of initial cost outlay and in system maintenance. This means that these networks will be based on Internet standards even if the systems remained independent of the global network conglomeration. Based on this assumption, the IP-based communication protocol was adopted for the FNET project.

Communications protocols are methods for transmitting data between networked computers. The most popular low-level protocol in use on the Internet is IP (the Internet Protocol). IP packages a data unit into an entity known as a packet and makes a best-effort attempt to deliver that packet to the intended destination. Best-effort here means that if a problem occurs in the delivery attempt, perhaps because of network congestion, then the packet will be lost. IP is rarely used by itself. Higher-level transport protocols run on top of IP to provide added functionality.

The two integral networking protocols in IP-based networks such as the Internet are the Transmission Control Protocol and User Datagram Protocol. TCP is the more popular of the two. TCP's most notable contribution beyond IP's functionality is its ability to compensate for network losses by retransmitting data until it has been received by its intended destination. This is extremely valuable in many cases, but it can have drawbacks in time-sensitive situations since TCP delivers all data on a first-come first-serve manner. This means that information that is no longer relevant can stand in the way of current data if packet losses become too great. UDP, by contrast, only makes minor additions to IP. UDP's best effort delivery guarantees can be a blessing in situations where data is only relevant for a limited time.

The server is designed for storage and displays the information from the dispersed clients, and is built on the technology of Network communication and Database. Communication is based on TCP/IP protocol. The server open the relative ports for clients, when the data coming, the socket process receives and then put it into database. FNET system is a two-way communication link between IMS server and FDR running via Internet. FDR collects the real-time frequency from the remote location, transmits the data to the IMS server. FDRCOM, which stands for FDR connectivity to IMS server, acts as a data communication bridge between the IMS server and FDR unit. In the current FNET system, FDRCOM is a communication device from a third party company. In the future generation, this device will be embedded in the FDR Unit, and multi-threading is used to process concurrent FDRCOM processes. In some places, due to the lack of network, wireless communication could be an alternate choice for data transmission. In this case, FDRCOM will make use of wireless modem to set up the connection to the IMS server.

In the server software design, communication is built on Windows Socket and use TCP/IP protocol based on client/server model. Although the current Internet is believed to lack reliability and latency guarantee to support real-time communication, many of the applications intended by FNET are not time-critical (e.g. observation, model validation, post-mortem analysis). The current network performance has proven to be very satisfactory for FNET. Low rate of missing data was experienced only from some units. Several FDR units have been in operation for more then one year. FDR redundancy can more than compensate for data transfer reliability. Furthermore, network providers are moving towards several crucial milestones in network evolution. It is expected the next generation of Internet should meet most of the real-time communication requirements.

### 2.4.3 Database Operation Service

The backend database is dedicated to data and file services that can be optimized without using any proprietary database languages. It provides a convenient mechanism for accessing the data. The historical storage consists of logged data, frequency disturbance events and real-time frequency data. Access to the database is provided through a series of interface modules that read and write data to the database tables. In the FNET system, ODBC is used for database manipulation. The data management component ensures that the frequency data is consistent throughout the distributed environment using features such as data locking, consistency, and replication. The database has these features:

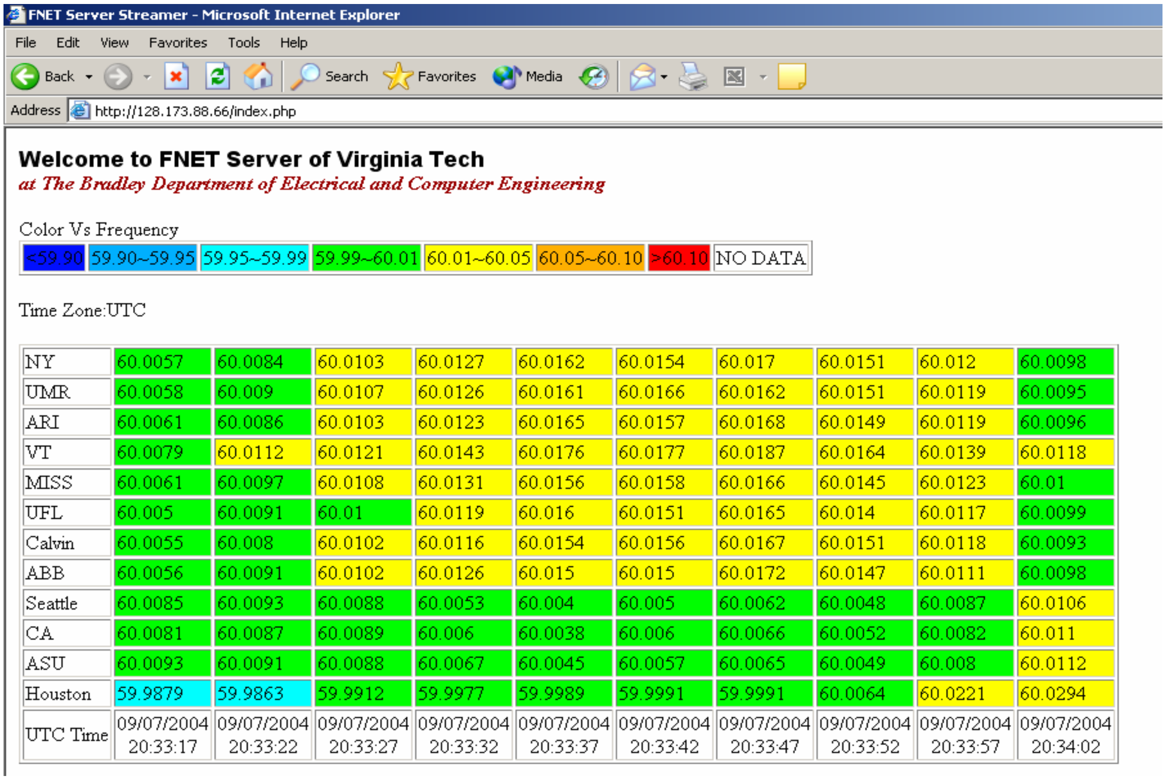
- Automatically storage frequency data from dispersed sites.
- Synchronize the frequency sampling intervals, time stamp information and any other time information required.
- Collect absolute frequency data to a resolution of four decimal.

- Archive frequency data for each of the interconnections at a minimum sampling rate of ten times per second maintaining a resolution of four decimal places.
- Maintain on-line archive frequency data as historical data.
- Include report production and database query capabilities that offer standard periodic reports and event driven reports based on archived data for each interconnection. These are subscriber reports that are automatically generated.
- Provide database query and report writing tools to generate both graphic and tabular format reports.
- Allow authorized users to view and query frequency database contents.

### 2.4.4 Web Service Interface

The web service integrates the frequency display, monitoring and historical data retrieval into a common easily accessible user interface [44-52]. When the user accesses the IMS web page, a security mechanism will be triggered to allow only the authorized user to access the real-time frequency information. Passwords are set at multiple levels to allow different users to access different levels of information. The functionality of the interface is only limited to viewing the overall frequency information of the system being monitored. Users accessing the interface do not take an active part in controlling the system on a continuous basis. The server pages are written in PHP and Java.

When the user logs in, the corresponding information is displayed in a tabular display using HTML format, as shown in Figure 2.6. The color of each cell corresponds with the value range of the frequency, so that this web page can give a direct image of the system frequency in the different locations of the power grid. At the same time, the web service also provides a curve observation window for each FDR unit. As shown in Figure 2.7, visitors can select the units they want to observe, and the real time frequency data of each unit is displayed.




| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NY | 60.0057 | 60.0084 | 60.0103 | 60.0127 | 60.0162 | 60.0154 | 60.017 | 60.0151 | 60.012 | 60.0098 |
| UMR | 60.0058 | 60.009 | 60.0107 | 60.0126 | 60.0161 | 60.0166 | 60.0162 | 60.0151 | 60.0119 | 60.0095 |
| ARI | 60.0061 | 60.0086 | 60.0103 | 60.0123 | 60.0165 | 60.0157 | 60.0168 | 60.0149 | 60.0119 | 60.0096 |
| VT | 60.0079 | 60.0112 | 60.0121 | 60.0143 | 60.0176 | 60.0177 | 60.0187 | 60.0164 | 60.0139 | 60.0118 |
| MISS | 60.0061 | 60.0097 | 60.0108 | 60.0131 | 60.0156 | 60.0158 | 60.0166 | 60.0145 | 60.0123 | 60.01 |
| UFL | 60.005 | 60.0091 | 60.01 | 60.0119 | 60.016 | 60.0151 | 60.0165 | 60.014 | 60.0117 | 60.0099 |
| Calvin | 60.0055 | 60.008 | 60.0102 | 60.0116 | 60.0154 | 60.0156 | 60.0167 | 60.0151 | 60.0118 | 60.0093 |
| ABB | 60.0056 | 60.0091 | 60.0102 | 60.0126 | 60.015 | 60.015 | 60.0172 | 60.0147 | 60.0111 | 60.0098 |
| Seattle | 60.0085 | 60.0093 | 60.0088 | 60.0053 | 60.004 | 60.005 | 60.0062 | 60.0048 | 60.0087 | 60.0106 |
| CA | 60.0081 | 60.0087 | 60.0089 | 60.006 | 60.0038 | 60.006 | 60.0066 | 60.0052 | 60.0082 | 60.011 |
| ASU | 60.0093 | 60.0091 | 60.0088 | 60.0067 | 60.0045 | 60.0057 | 60.0065 | 60.0049 | 60.008 | 60.0112 |
| Houston | 59.9879 | 59.9863 | 59.9912 | 59.9977 | 59.9989 | 59.9991 | 59.9991 | 60.0064 | 60.0221 | 60.0294 |
| UTC Time | 09/07/2004 20:33:17 | 09/07/2004 20:33:22 | 09/07/2004 20:33:27 | 09/07/2004 20:33:32 | 09/07/2004 20:33:37 | 09/07/2004 20:33:42 | 09/07/2004 20:33:47 | 09/07/2004 20:33:52 | 09/07/2004 20:33:57 | 09/07/2004 20:34:02 |

Figure 2.6 Streamer table of real-time frequency

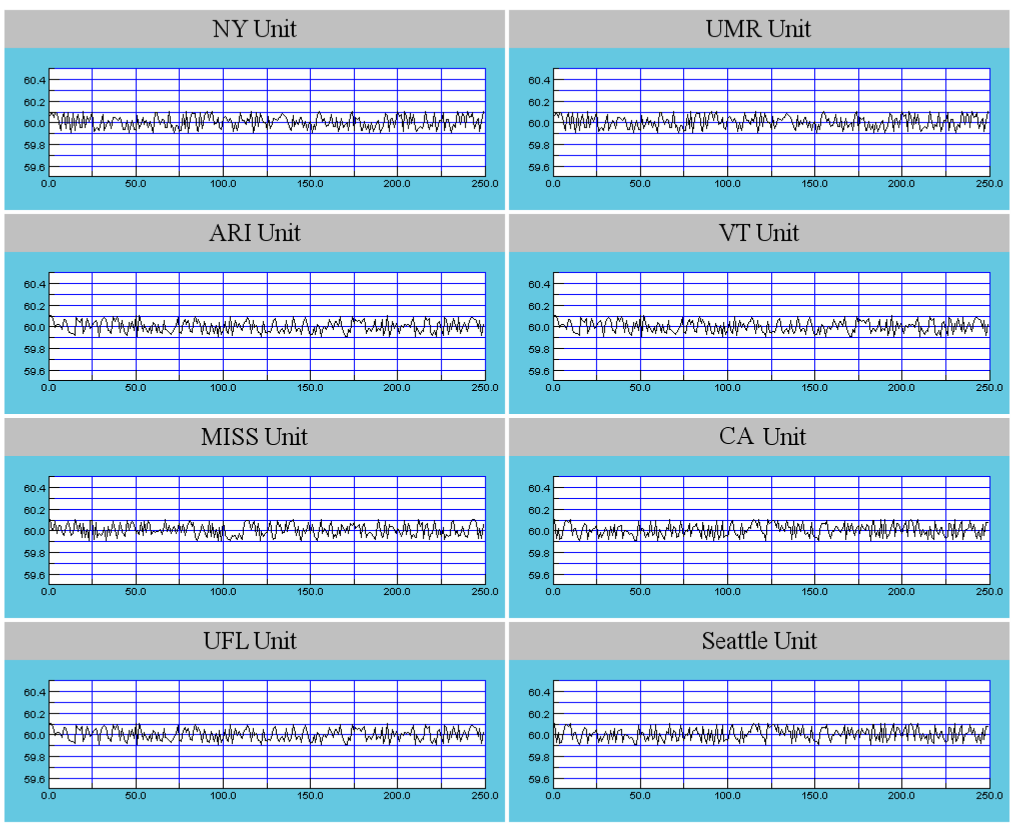



Figure 2.7 Observation window of real-time frequency

In addition, a frequency interpolation map (see Figure 2.8) is provided for viewers to experience a visualization image of the frequency information in a geographic context.

The dynamic frequency data visualization contains three steps: area tessellation of frequency variation; frequency data interpolated shading; data rendering and animation. Rendering the power system frequency in a geographic map is a good approach for visualization of large amounts of data. Frequency image interpolation shows the distribution of the frequency in the continental United States. The color margin is the same as what is in the frequency streamer display, and the black points in the map are the locations of the FDR units.

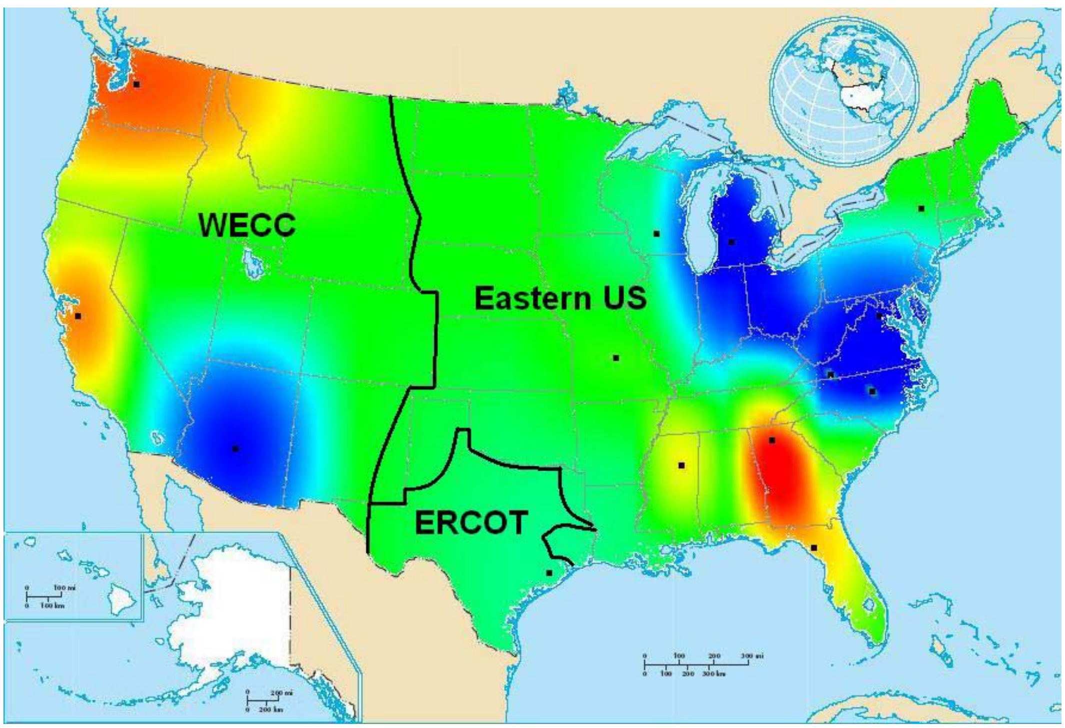



Figure 2.8 Frequency dynamic data visualization map

## 2.5 Frequency Monitoring Network Implementation

### 2.5.1 Frequency Disturbance Recorder Placement

The FDR units are used to record the dynamic frequency information for power system analysis and control. The location selection for FDR units is an important issue for the

FNET system. The locations should effectively reflect the different frequency clusters of inter-area oscillations and cover as broad an area as possible in order to capture dynamic behavior of larger system disturbances. Just like PMU placement analysis [53], FDR placement should represent the system frequency, effectively describe the behavior of major inter-connected systems, and provide information on the large area load behavior.

As we know, there are 10 regional Reliability Councils whose members come from all segments of the electric industry: investor-owned utilities; federal power agencies; rural electric cooperatives; state, municipal and provincial utilities; independent power producers; power marketers; and end-use customers [54]. These entities account for virtually all the electricity supplied in the United States, Canada, and a portion of Baja California Norte, Mexico. Among these 10 regions, ERCOT and WECC are independent interconnections, and the other eight regions, (ECAR, FRCC, MAAC, MAIN, MAPP, NPCC, SERC, and SPP) construct the Eastern US Interconnection (EUS) as shown in Figure 2.9. The goal of FNET is to cover all the regions of these 10 regions and there should be at least three geographically and electrically separated FDR within each of the Interconnections and Hydro Quebec.


Figure 2.9 NERC regions and sub-regions map [54]

Presently, the FDR locations were selected to cover the power grid of North American divisions. In the FNET system, more FDR units can be located close to major generation centers, major transmission tie lines and load concentrated areas for mode studies of the local frequency oscillation. The FDR units can be easily relocated, since it is plug-and-play with no installation cost involved.

As of July of 2005, we have deployed 15 FDR units distributed in US, as shown in Figure 2.10. Among them, four units are in WECC, one unit is in ERCOT and 10 units are in the EUS. Current FDR deployment in the EUS has covered five reliability councils. Additionally the IMS is set up at Virginia Tech. The number of FDR units will increase to cover the entire US power grid, and there will be approximately 20 FDR units in the FNET system in the near future. In the figure, the node with a colored tag is where the FDR unit is located and the node without tag is future FDR location. The color tag reflects the range of the frequency of each unit at different locations. FNET is an ongoing project and we anticipate more FDR units will be deployed into the system.

Table 2.1 FDR Unit Location and Relative Council

| Unit ID | Unit Name | Reliability Council | Location |
|---|---|---|---|
| 1 | NY | NPCC | Schenectady, NY |
| 2 | UMR | MAIN/SERC | Rolla, MO |
| 3 | ARI | SERC | Alexandria, VA |
| 4 | VT | ECAR/SERC | Blacksburg, VA |
| 5 | Seattle | WECC | Seattle, WA |
| 6 | ABB | SERC | Raleigh, NC |
| 7 | MISS | SERC | Starkville, MS |
| 8 | CA | WECC | Palo Alto, CA |
| 9 | UFL | FRCC | Gainesville, FL |
| 11 | Calvin | ECAR | Grand Rapids, MI |
| 12 | ASU | WECC | Tempe, AZ |
| 14 | Houston | ERCOT | Houston, TX |
| 16 | LA | WECC | Los Angels, CA |
| 17 | TLN | SERC | New Orleans, LA |
| 20 | TVA | SERC | Huntsville,TN |

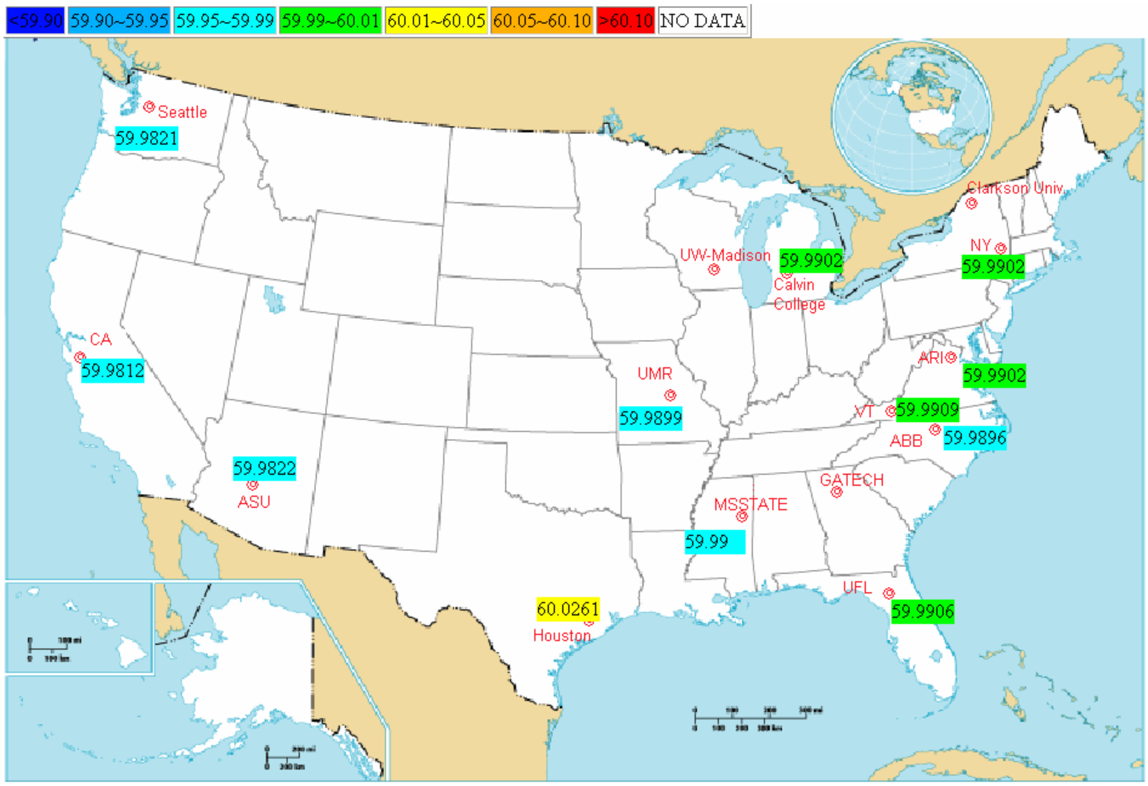



Figure 2.10 Frequency Disturbance Recorders Location in Continental US Area

### 2.5.2 FNET Server Hardware and software configuration

The server receives data from different FDR units, processes the data, manages the database, performs data analysis, and supports the web service for the Internet users. The frequency IMS server can be physically located anywhere, which is with the following system configurations:

a) Hardware configuration: A dual CPU (Intel Pentium 4 CPU 3.6GHz) server with a hard disk (500GB) is employed to meet the need of reliable data transmission, processing and web service. The backup data is stored both on the hard disk of the server and in an external hard drive.

b) Server software configuration: Windows XP 2003 Server is the host operating system. A commercial database is installed at the database server machine, as the backend database. C++ is employed for the whole server program design and communication. Internet standard web browsers are used as the interface for the user to access the frequency data.

### 2.5.3 Assessment of Server Handling Ability of units

For the server, due to the limitation of hardware and software, the maximum unit number, which can be handled by the server, need be assessed. In this section, a client program, which has the same function as a real FDR, will send random data to the server to test under the normal condition how many units can be handled simultaneously. The testing program is named as Virtual_FDR.

There are some possible limitations of the server:

- communication limit
- server CPU limit
- server memory limit
- server database write limit

Virtual FDR send the data package, which include UnitID, time_Date, currentTime, convNum, firstFreq, finalFreq, voltageMag, voltageAng, to the server. From the server side, the Virtual FDR is the same as real FDR unit, and the only difference is that real FDR unit sends data from different IP address, while all V-FDR send data from the same IP address. This difference affects the evaluation of communication limit.

In the test, one computer served as server, open N socket port to wait for the data coming, while another computer served as client of V-FDR, and open N socket connection to the server and send data through these socket connections. The number of socket connection can be set and it is what the limitation test needs to know.

The server hardware: CPU, duel 3.4GHz Intel Pentium 4; Memory, 1GByte of RAM
The client hardware: CPU, 3.4GHz Intel Pentium 4; Memory, 1GByte of RAM

In the test, first set the number of V-FDR as 20, and then increase the number by 10 to get the maximum number of V-FDR that the server can handle.

We found that the main limitation is the CPU time, when the number grows up to 60, the server's CPU time will grow up to 50%; when the number increases to 70, the server can still handle it; while when the number becomes 80, the server can't receive any data and is just stuck. Because the server program is a single-thread program, so it can only occupy one CPU at most and this equal to 50% of the total CPU time.

Table 2.2 CPU Usage in Handling Limit Test

| Num of Units | CPU Time(Average) | Peak CPU Time |
|---|---|---|
| 0 | 0% | 1% |
| 20 | 18% | 22% |
| 30 | 25% | 27% |
| 40 | 32% | 34% |
| 50 | 40% | 43% |
| 60 | 50% | 52% |
| 70 | 50% | 52% |

From this testing, we can get a conclusion that a normal PC with the previous defined setting can handle 70 units simultaneously, and the bottleneck is from CPU. With the effective modification to the server code, it handles more units, while if the unit number grows to the level of hundreds; the CPU should be upgrade to a more powerful workstation CPU.

## 2.6 Summary

FNET stands for frequency monitoring network. The system implements WAMS in a way that the frequencies of the whole US & Canada power grid can be collected and managed in a central server. Continuous synchronized wide area frequency information will provide system operators with near real-time system status. Here, by "near real-time" we mean less than 1-2 seconds delay for most of the data. FNET will help to detect system disturbance, to perform post disturbance scenario reconstruction, to verify system models and parameters used in simulations, and to track the sequence of events leading to an emergency.

FNET has the following special features: (1) Nation-wide system frequency information (and phase angles) can be collected from hundreds of key sites chosen to satisfy observability and controllability criteria. (2) The measurements will be taken at 110V single phase power outlets to avoid costly substation installation. (3) Time stamped frequency data will be collected via Internet on a continuous basis in near-real time. (4) Standard frequency disturbance recorders (FDR) will be used in all measurement sites to guarantee convenient data integration and comparison.

As of June of 2005, we have deployed 15 FDR units across U.S. Among them, four are in WECC, one unit in ERCOT and 10 units in the EUS.

FNET provides valuable data for studies of inter-area oscillations, disturbance analysis, scenario reconstruction, and model verification. Researchers hope to use the data from a nationwide FNET system to forecast incipient system breakups and recommend remedial actions. The continuous synchronized information from the FNET system will provide system operators all over the country with close to real-time system status so that they can better manage the grid and for analysis after a system disturbance. The real-time wide-area frequency information can be used in many areas to perform control and protection functions. The FNET system provides power system researchers, operators, customers, and policy makers a relatively easy to access, cost-effective, cross-platform frequency information monitoring network on the Internet.

# Chapter 3 Frequency Disturbance Recorder Testing and Comparison with PMU

## 3.1 Comparison of Frequency from PMU and FDR

In order to verify the accuracy of the frequency measurements of the FDR unit, a comparison was carried out in 2003 between a FDR unit and commercial PMUs (Phasor Measurement Unit). The commercial units come from four different manufacturers.

The test used the four PMUs and one FDR unit to connect to the same phase voltage signal from a wall outlet. This method ensures that all these devices measured the frequency from the same voltage wave. The measured raw frequency data were stored the in unique files as each device defined. The output frequency data from all these units were compared. Actually, the output rate of each PMU is different, so different units will have different number of frequency data points per second.

Synchronization of sampling was achieved with a common timing signal available locally at the substation. The phasor calculations demand greater than the 1-millisecond accuracy. It is only with the opening for commercial use of GPS that phasor measurement unit was finally developed. GPS is capable of providing timing signal of the order of one microsecond at any locations around the world. It basically solved the logistical problem of allocating dedicated land based links to distribute timing pulses of the indicated accuracy. Reference [55] presents a detailed analysis of the required synchronization accuracy of several phasor measurement applications.

### 3.1.1 Short Period Frequency Comparison

The following figures (3.1~3.5) show the results of the PMUs and the FDR for a period of 15 seconds. The frequency data, which was measured at the same selected period, will be output to the particular raw data format. Mablab is used to make the plot of raw frequency data. The comparison of this section was taken on Sept.9 2003.

Given that true system frequency should not change suddenly under any circumstances, it is clear that the accuracy of the FDR is more refined compared to the commercial PMUs. Note that the FDR data shown are raw (not filtered), and the PMU plots given are already filtered using limiters. The cut-off effects of the limiters in Figure 3.1, Figure 3.2 and Figure 3.3 are visible.

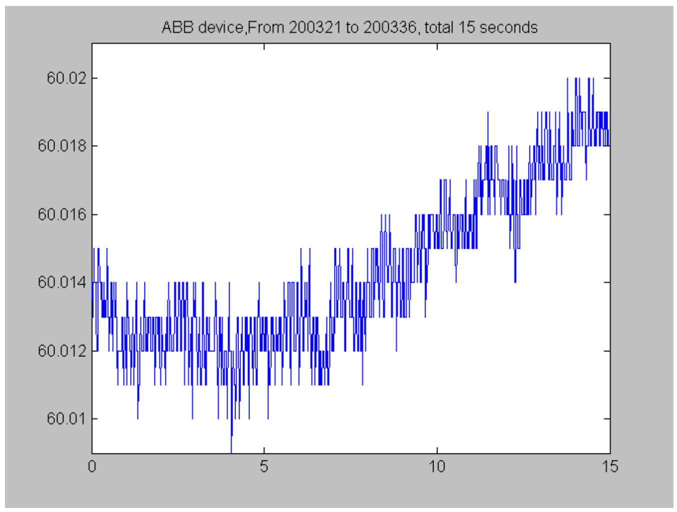



Figure 3.1 Limiter Filtered Data from PMU A

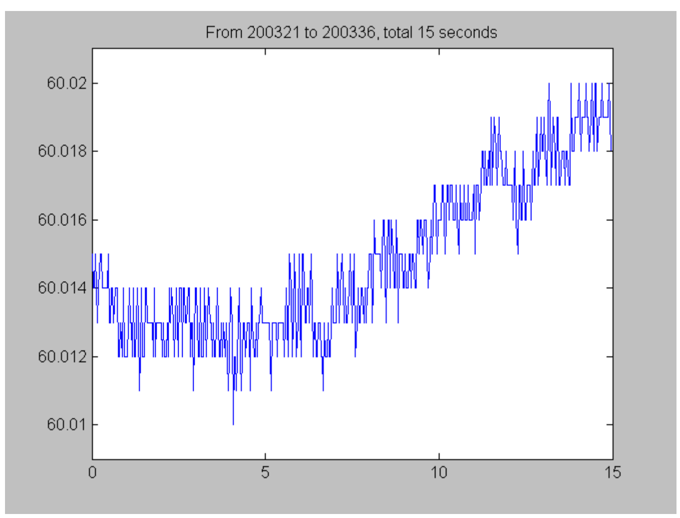



Figure 3.2 Limiter Filtered Data from PMU B

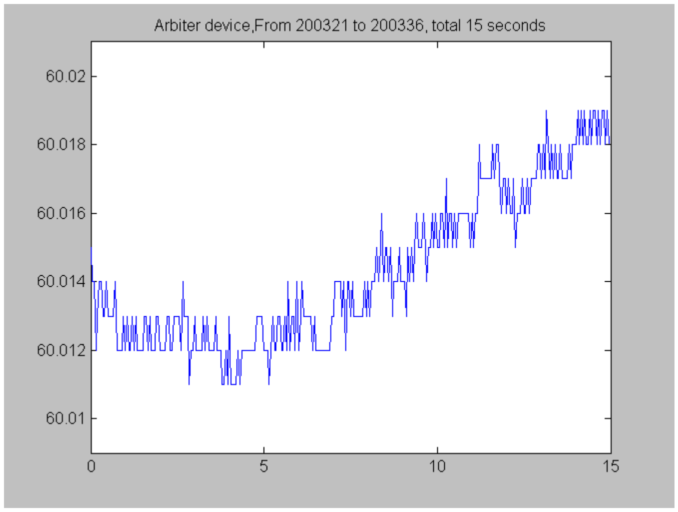



Figure 3.3 Limiter Filtered Data from PMU C

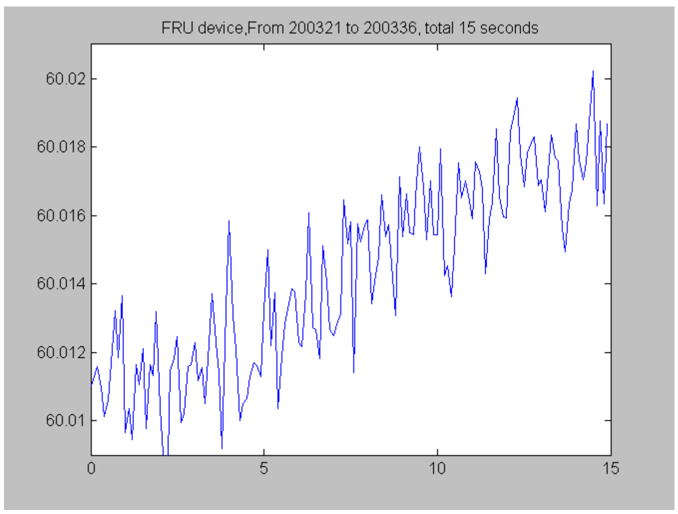



Figure 3.4 Unfiltered (Raw) data of FDR

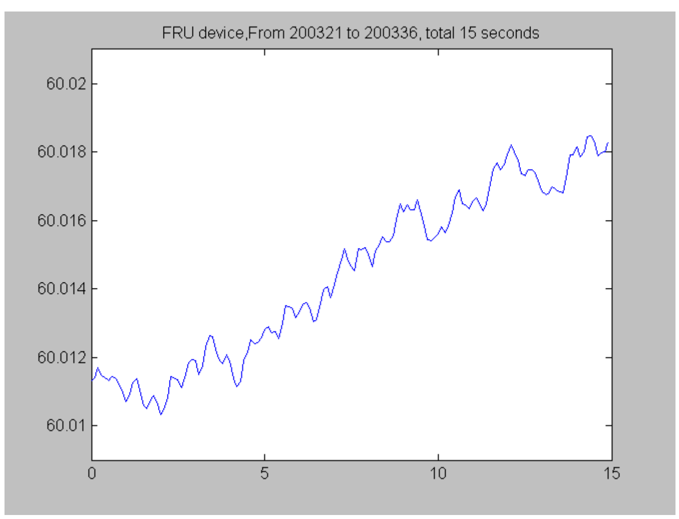



Figure 3.5 Unfiltered data of FDR (using the current algorithm, 8-point average)

In this section, another period frequency plots were compared, and this time all four PMUs recorded the frequency.

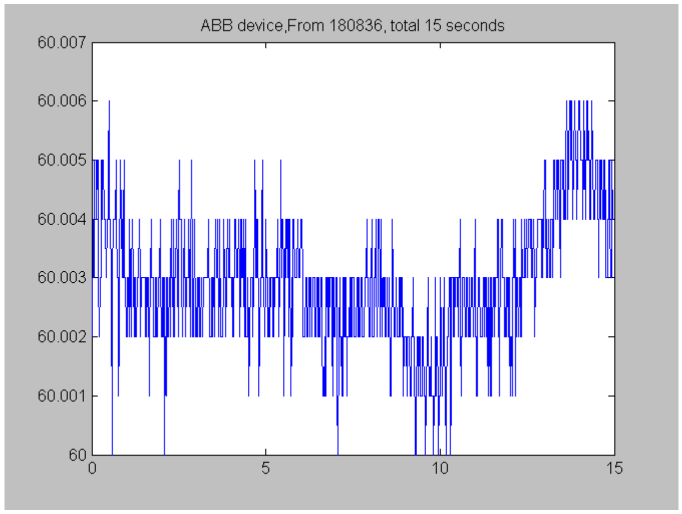



Figure 3.6 Limiter Filtered Data from PMU A

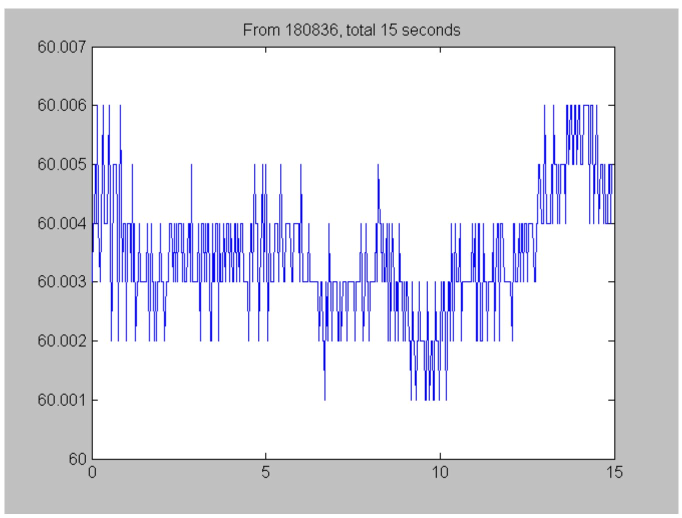



Figure 3.7 Limiter Filtered Data from PMU B

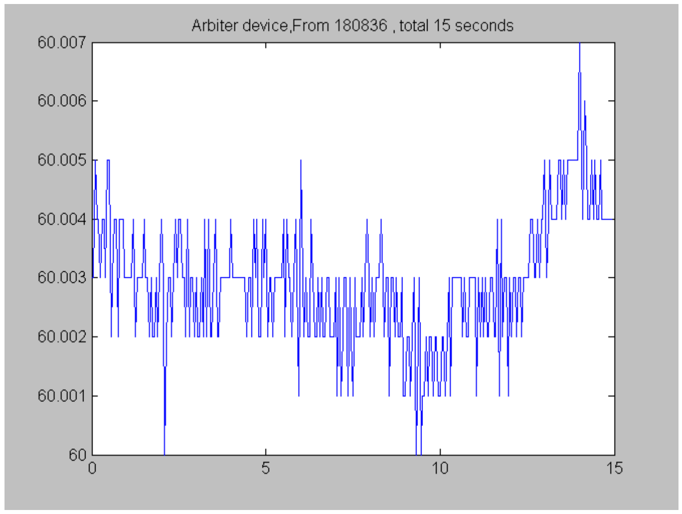



Figure 3.8 Limiter Filtered Data from PMU C

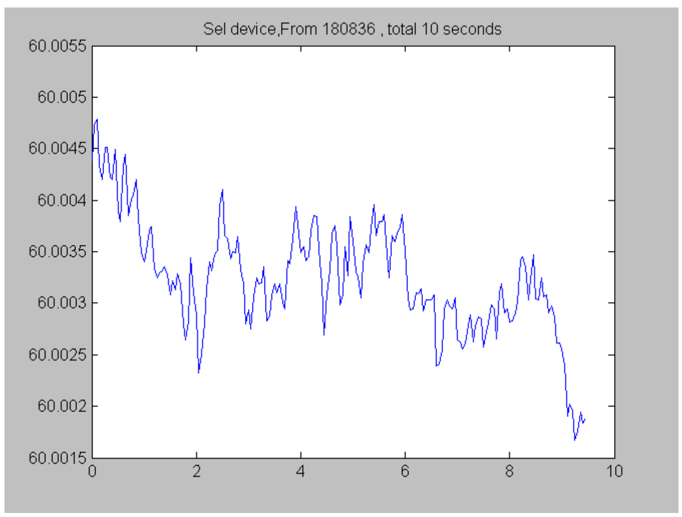



Figure 3.9 Limiter Filtered Data from PMU D

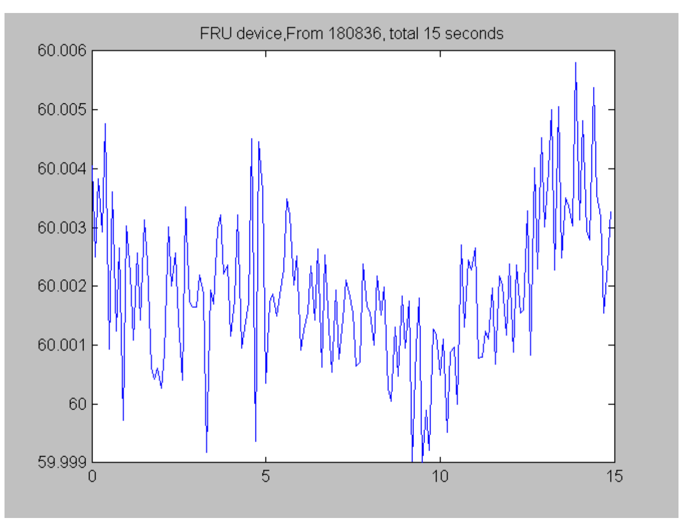



Figure 3.10 Unfiltered data of FDR

### 3.1.2 Long Period Comparison Result

This section gives a long period comparison between FDR and PMU measurement, because some of the PMU cannot record data for a long time, so here only the result form PMU A, PMU C, and FDR can be compared. In the following three plots, there are totally around 567 seconds frequency data from each unit.

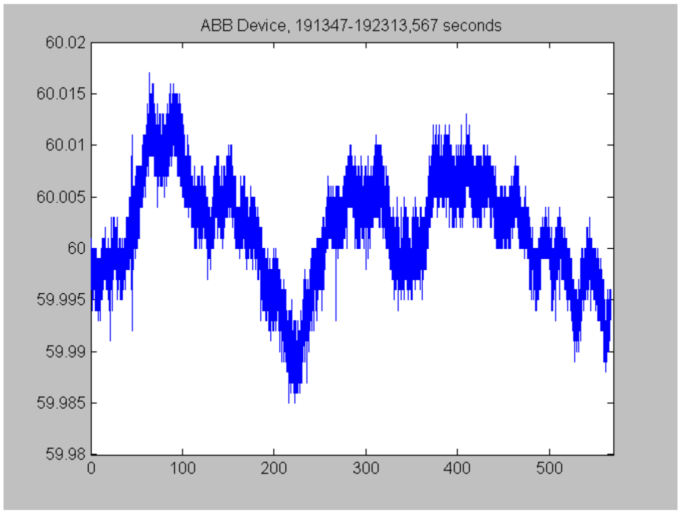



Figure 3.11 Limiter Filtered Data of PMU A (long term)

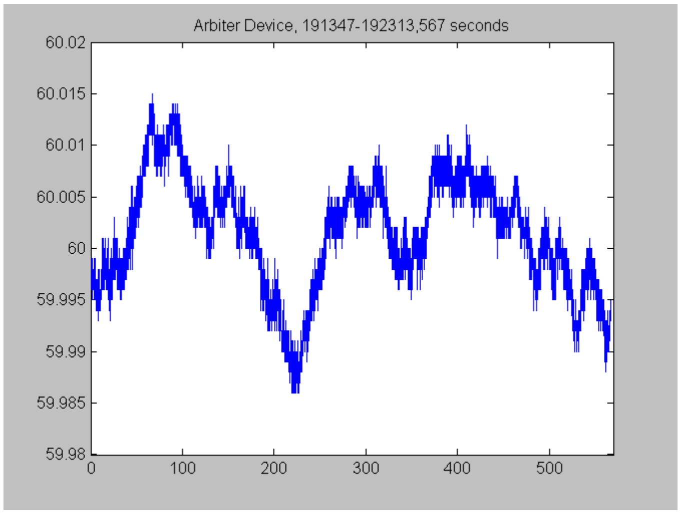



Figure 3.12 Limiter Filtered Data of PMU C (long term)

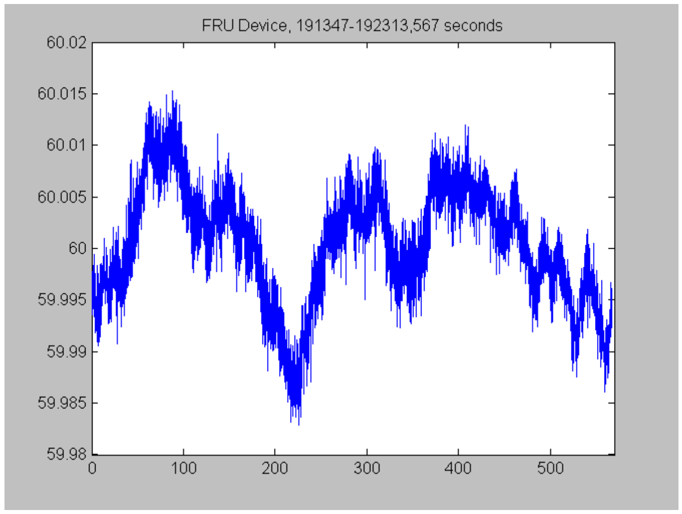



Figure 3.13 Limiter Filtered Data of FDR unit (long term)

### 3.1.3 Comparison of Dynamic Response of FDR and PMU

This section uses function generator as feed-in signal, then manually change the output frequency. Firstly, change the frequency at the scale of 1 Hz, and recorded the frequency, then change the frequency at a much smaller scale. This comparison is to test the dynamic response of PMU and FDR can match each other. From the following three plots, it is very clear that all of them are accurate when the frequency of input signal changes in the range of 57Hz~63Hz.

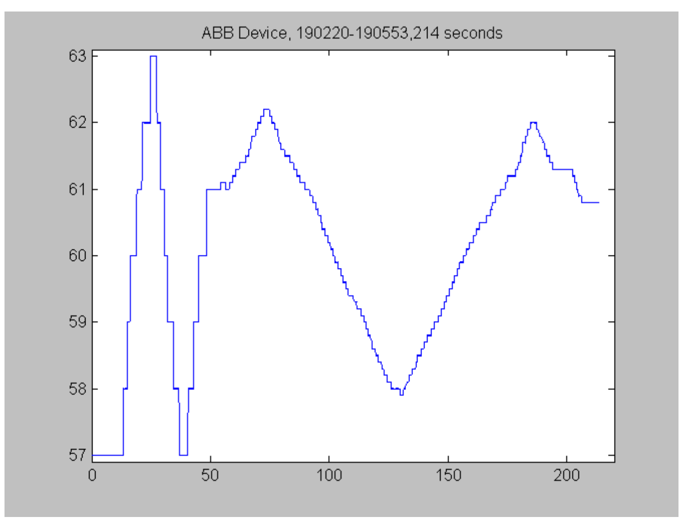



Figure 3.14 Dynamic frequency response of PMU A

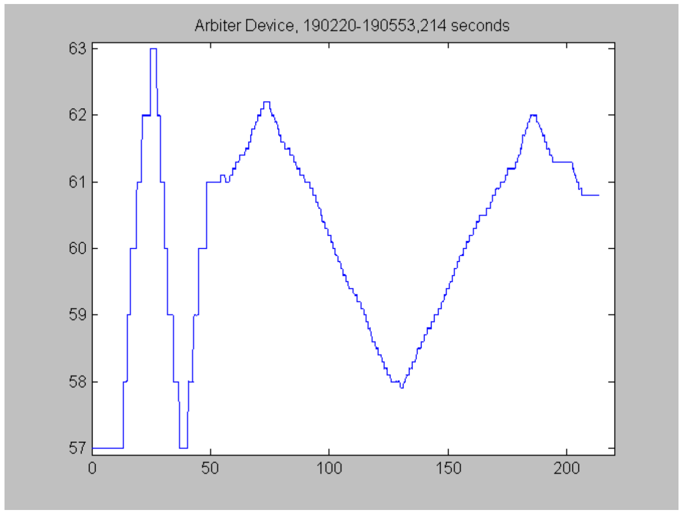



Figure 3.15 Dynamic frequency response of PMU C

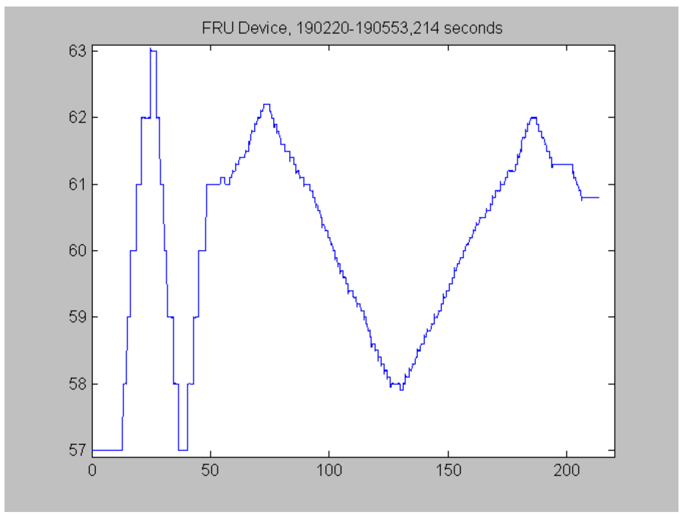



Figure 3.16 Dynamic frequency response of FDR unit

### 3.1.4 Frequency Disturbance Recorder Accuracy Verification

Another study to test the accuracy of FDR units is applying a comparison between two FDR units, which measured the same signal from wall outlet. The frequency records (Figure 3.17) showed that the frequency from two units could match each other. The difference of two FDR units is calculated (Figure 3.18), and the curve looks like modulation. First, calculate the difference between two units at every point and this gives a sequence of error. Then, calculate the mean and the standard deviation (STD) of this sequence, the range can be derived as: $max = mean + 3 \times STD$ , $min = mean - 3 \times STD$ ; so, if most (say 99%) difference is in this range, and the range is acceptable (say, $\pm 0.008Hz$), so that the error between two FDR units is actually very small.

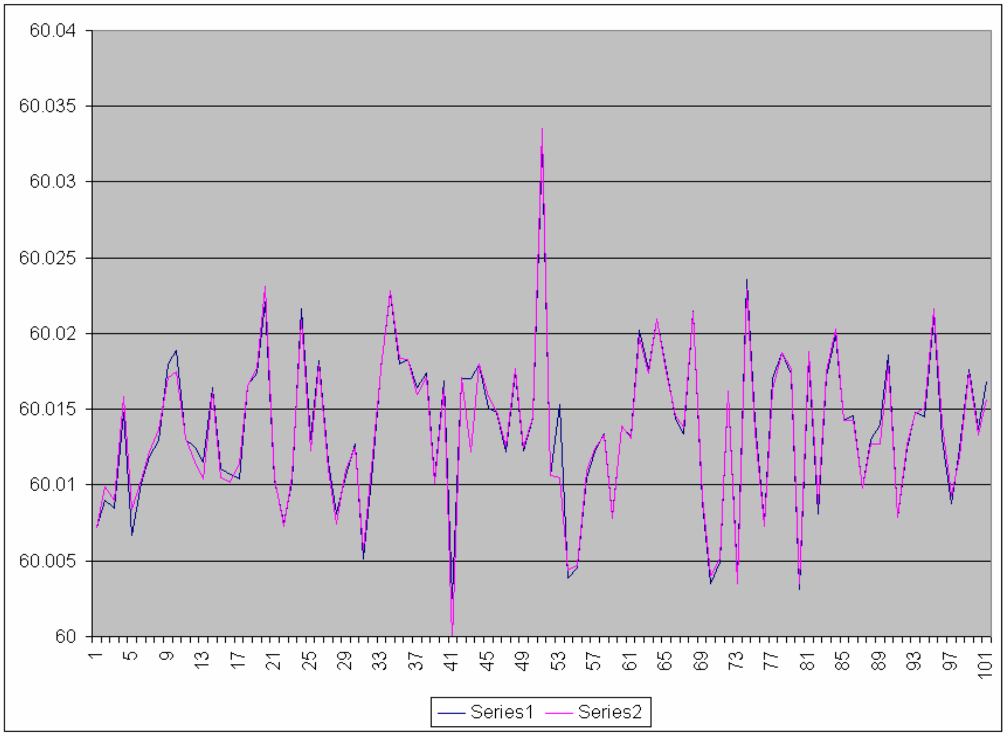



Figure 3.17 Frequency Records Comparison of two FDR Units

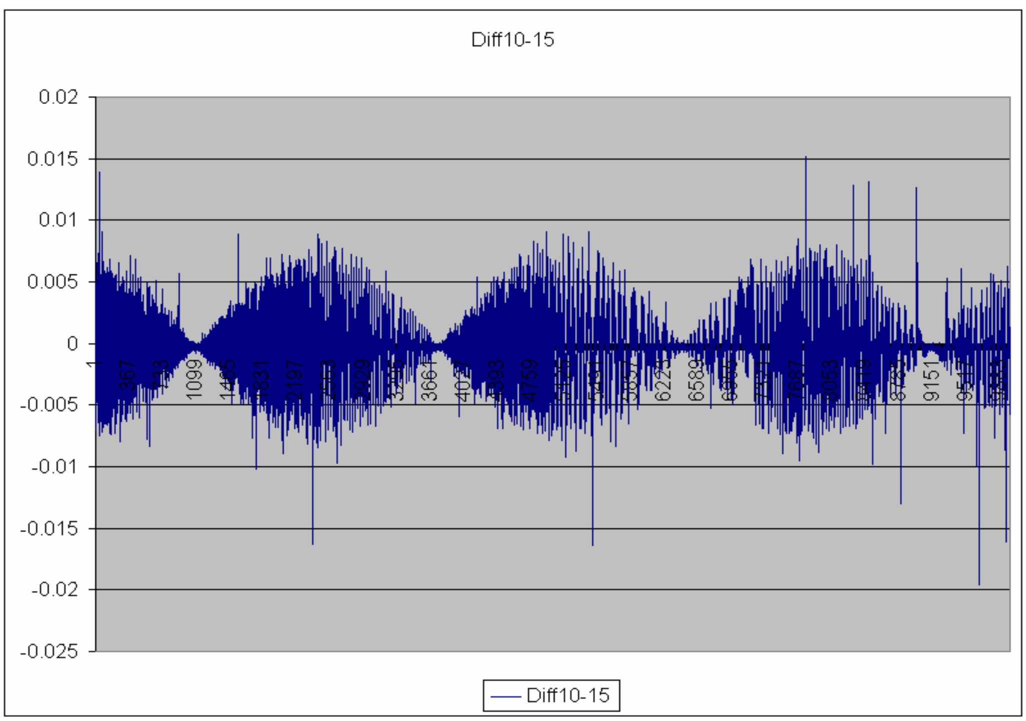



Figure 3.18 Frequency Difference between two FDR Units

### 3.1.5 Test of Accuracy with the Fixed Input Signal

This section is to use the accurate 60 Hz signal from signal generator to feed in the frequency measurement devices. Because the input signal is from very accurate device, so the result from PMU and FDR should exactly match each other if they are accurate as what they are claimed to be.

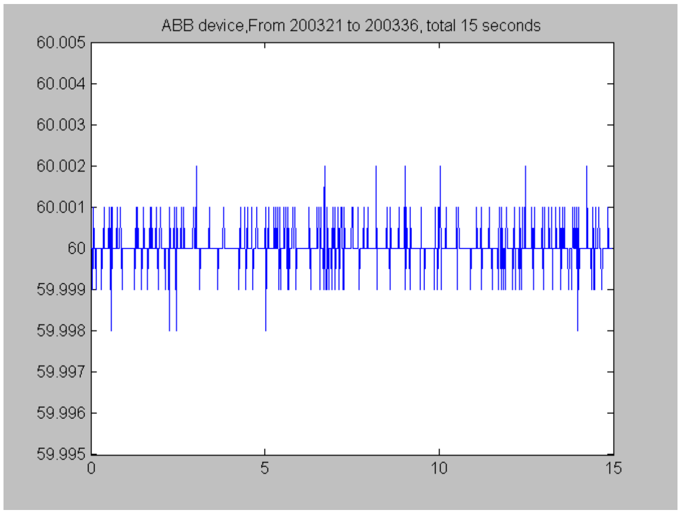



Figure 3.19 Measured frequency data of PMU A with accurate 60 Hz signal

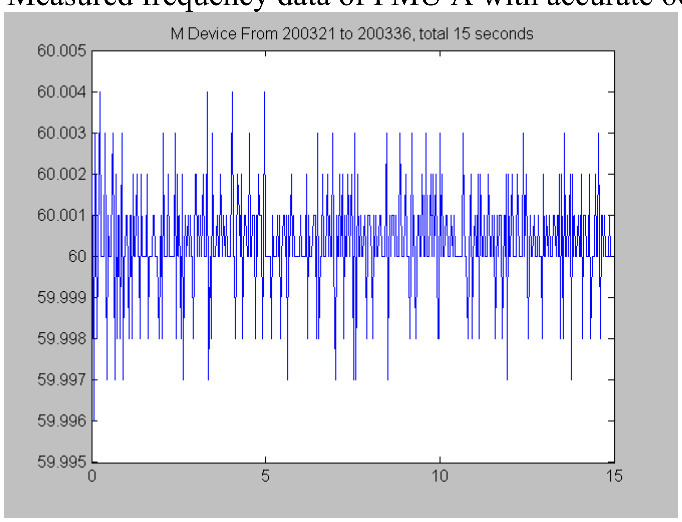



Figure 3.20 Measured frequency data of PMU B with accurate 60 Hz signal

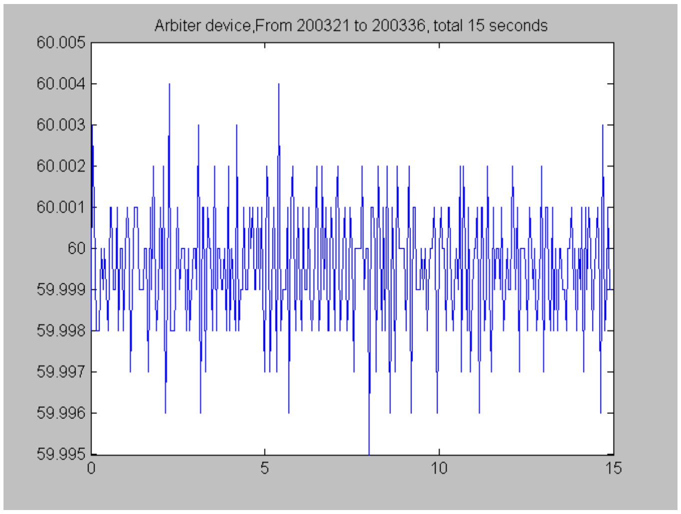



Figure 3.21 Measured frequency data of PMU C with accurate 60 Hz signal

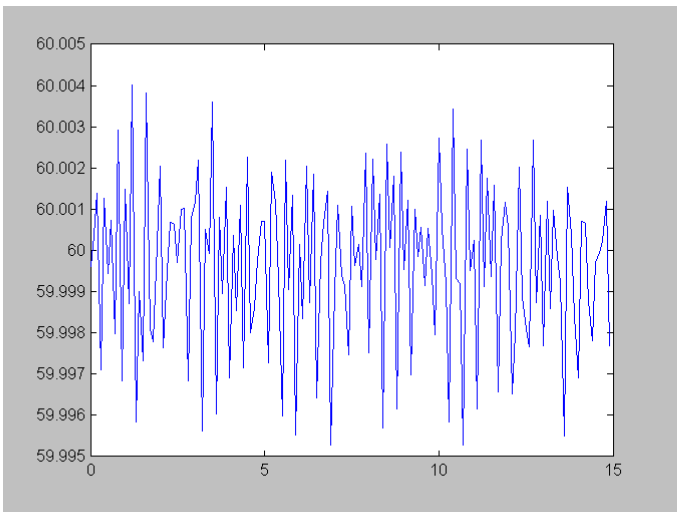



Figure 3.22 Measured raw frequency data of FDR unit with accurate 60 Hz signal

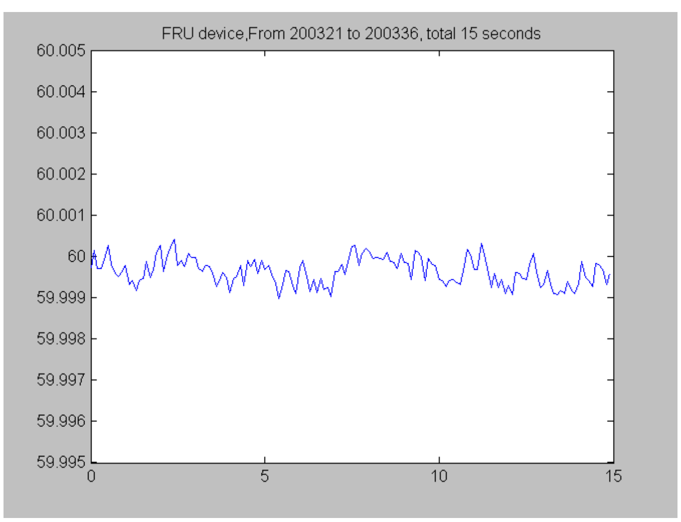



Figure 3.23 Measured average-frequency data of FDR unit with accurate 60 Hz signal

## 3.2 Multi Re-sampling (MR) Algorithm

The second generation FDR, currently under testing, will see a major accuracy boost as a result of a new multi re-sampling (MR) technique. As shown in Figure 3.24, the current algorithm in FDR has zero algorithm error at 60 Hz, but with the MR technique, the error could be made to reach zero for a much wider frequency range. Several new filtering techniques are also being tested and implemented to account for local noise at distribution level.

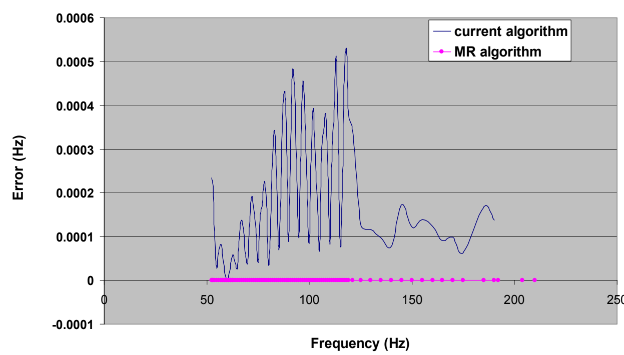



Figure 3.24 Accuracy comparison of current and next generation algorithms

## 3.3 Summary

The FDR unit built at Virginia Tech uses the same frequency calculation phasor algorithm with PMU, and some modifications are added to ensure the FDR can work with 110 V signal. This chapter gives comparison result between FDR and PMU, which illustrate that FDR can get the required accuracy and has the advantage of low cost, fast deployment and so on. The comparison shows that the Frequency Disturbance Recorder can monitor the frequency of power system and has the same accuracy compare to PMU.

# Chapter 4 Frequency Pattern Analysis of the US Power Grids

## 4.1 Introduction

Because FDR has the ability to record the frequency and send to the server continuously, so after the FNET system running for more than one year, bulk of field-measure frequency data is available for further analysis to system behavior. In this chapter, many analysis of the frequency can be processed with some mathematical program, including general system frequency pattern, characteristics of frequency deviation of each interconnection, statistical analysis of frequency, frequency shift in distribution system, area frequency oscillation and so on.

The frequency recorded by FDR is able to reflect both system dynamics and local variation dynamics. Local load change and switching typically introduce spikes in frequency measurement. Actually, FNET is trying to observe and analyze the system level dynamics, therefore, the local variation effect should be removed with some mathematical method and so system's dynamics can be better observed. Raw historical frequency data is stored in the database file of Microsoft ACCESS 2000; some processing programs are designed to facilitate the mathematical analysis. Please refer to section 2.5.1 for the locations of units mentioned in the section.

## 4.2 Local Frequency Characteristics

In this section, the frequency from different units is observed and compared to illustrate the frequency behavior of the system. A sample of FDR raw data from ARI unit is shown in Figure 4.1. From the plot of frequency, it is clear that the power system frequency does not hover around 60 Hz, but crosses above and below this value to keep the running average close to nominal frequency.  Since frequency represents the electromechanical characteristics of the power system, it does not suppose to vary rapidly, while there are sharp spikes and noises in the frequency measurement. These sharp spikes and noise are mostly caused by rapid and random local load changing at the distribution level, the inadequate power quality of the local system and/or other unknown noises polluting the measurement data. In addition to these sharp spikes, there are outliers, for which the frequency is out of the normal frequency range. These outliers can be caused by measurement errors or other unknown reasons. The outlier shows as sharp spikes between adjacent points and the outlier is not related to the system dynamics. Therefore, before the raw frequency data feed into the further process, these kinds of noise and outlier should be removed. Here the small noise can be removed by moving average method, and outlier can be replaced by the average data of adjacent points. The following FDR frequency data will be processed to eliminate spikes and unwanted noises to better represent the FDR frequency data.

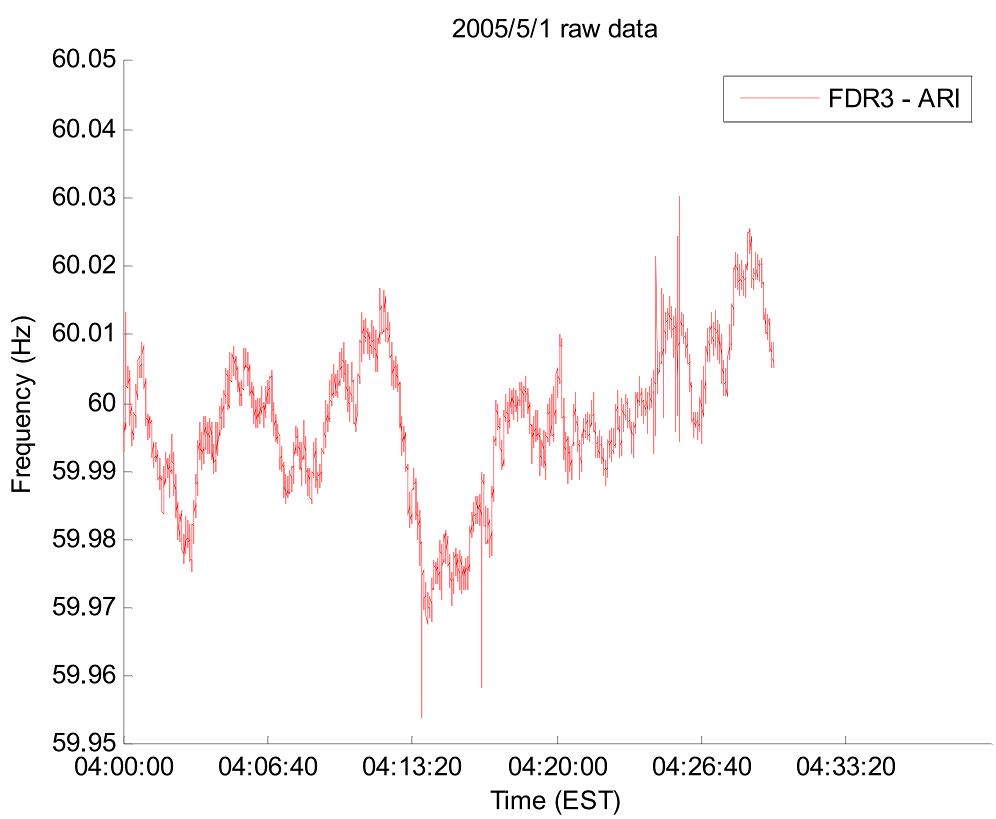



Figure 4.1 Raw Frequency data from ARI unit

### 4.2.1 Steady Status Frequency Comparison in Three Interconnections

In this section, the general operating frequency of the FDR units located in EUS, WECC, ERCOT are analyzed, and the difference of the filed-measured raw frequency data is compared.

EUS is the largest power grid interconnection in US, and most of FDR units are located in EUS, here the following figure shows the normal frequency in steady status. In order to make the frequency wave smoother to analyze, here the 10-point moving average is applied to the raw frequency data.

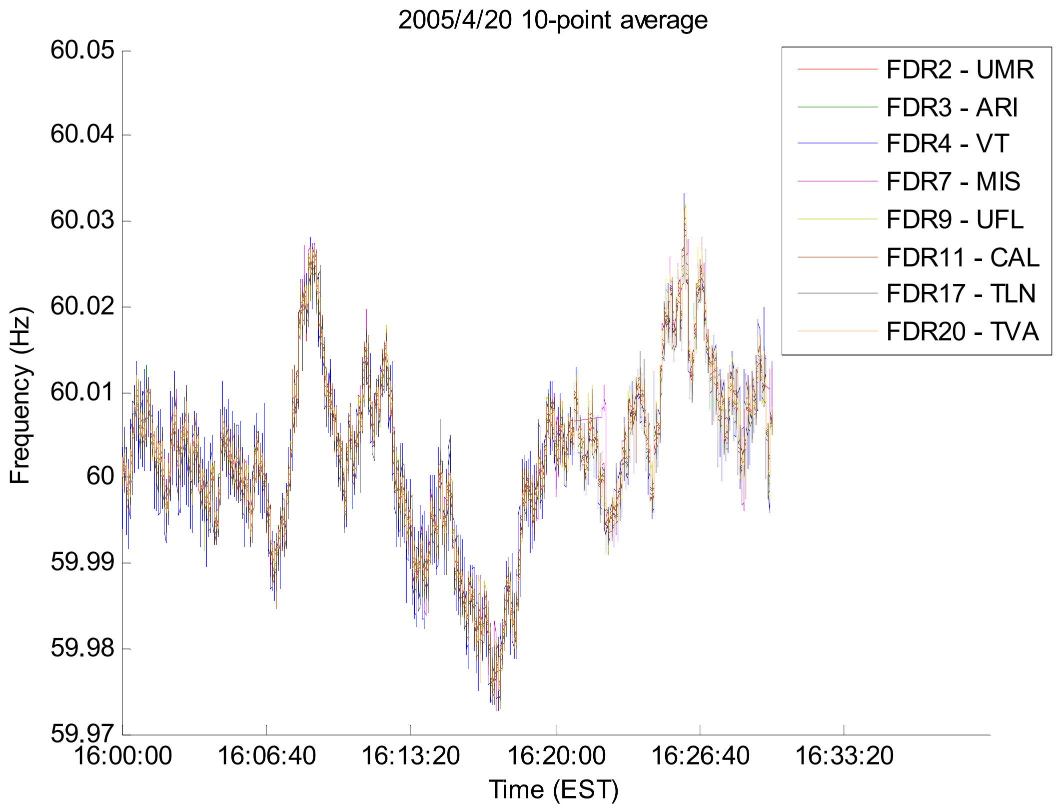



Figure 4.2 10-point Average Frequency plot in EUS

From the plots, we can see that the frequency of different locations in EUS have a little bit difference between each other, while the fundamental trend of frequency is the same at all locations in the same interconnection when the system is in steady status.

Then the plot of frequency in WECC at the same period of EUS is given in Figure 4.3, which illustrate that the frequency of WECC are synchronized better than EUS because the plots can almost cover each other.

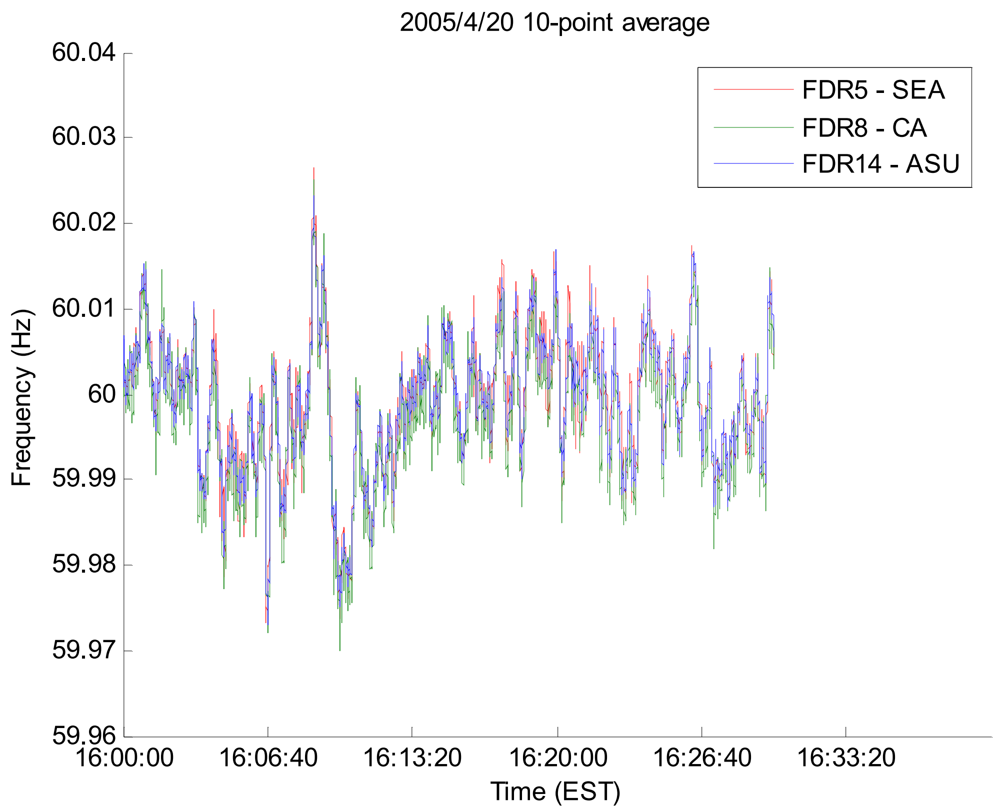



Figure 4.3 10-point Average Frequency plot in WECC

Then the turn goes to ERCOT, the smallest interconnection in North American power grid, and the plot of frequency in ERCOT at the same period of EUS is given in Figure 4.4. There is only one unit located at Houston in ERCOT area, so there is no other unit to compare with it currently. In addition, because the ERCOT is relatively small in aspect of capacity, the frequency response is relatively more fluctuating.

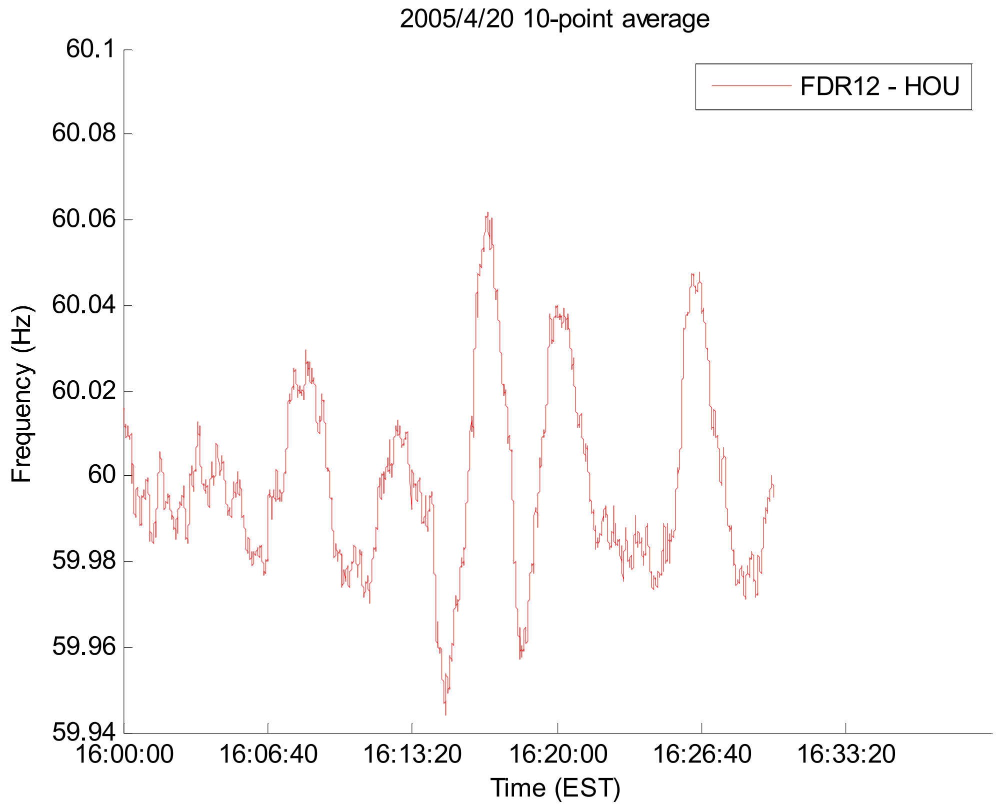



Figure 4.4 10-point Average Frequency plot in ERCOT

### 4.2.2 Frequency Comparison between EUS, WECC and ERCOT

From the comparison of frequency plots, the conclusion can be drawn that the frequencies of different locations in the different power systems have the different trends in steady status. Because the first four units are in the same power grid, the frequency trends of these four units are almost the same as each other, and so in the figure the curves cover each other. While the frequency from WECC system is quite different from these four ones, and we can find out that the frequency of this unit is mostly in the range of 59.98 to 60.02 Hz, so the regulation of WECC seems better than EUS. While because ERCOT is much smaller than these two interconnections, the frequency is very sensitive to the power balance, and so any small fluctuation of power will lead fluctuation of frequency.

## 4.3 Analysis of Frequency Shift: from Substation to Local Distribution System

PMU is designed to monitor the static and dynamic system status of power system, so most of PMU is installed at the high voltage buses to avoid the phase shift and other disturbance from local system. While the FDR is designed to install at the local low-voltage level system to avoid the installation issues, and so make the wide area observation of the power grid more affordable and applicable. The question comes: how can the measured frequency at 110 V outlets observe transmission system's dynamics? The frequency is typically not affected by the voltage transformation, i.e. on the same line with multiple transformers; the frequency stays the same from one point to another. The underlying assumptions of the FNET are that it can observe system's dynamics at the distribution at low cost and the measurement can be separated from local noises. There is a need to discuss the phase shift impact in the calculation of frequency propagation from high voltage level to local distribution power system. This analysis also reveals how the measurement from local 110V level represents the system level status. The analysis is processed in both of software simulation and real system observation.

### 4.3.1 Software Simulation of Frequency Shift Effect

PSS/E is the selected software to analysis the dynamic frequency response in this research work, and some other topics related to software simulation are also done with PSS/E in the following chapters.

The simulation is to observe the difference of frequency response between major high voltage buses and the low voltage buses in distribution system. The simulation is carried out with EUS system model provided by TVA, and the selected buses to be compared. Actually, because FDR is connected to the local system, and the simulation system model do not have detailed distribution system structure, so the analysis method is to use major high voltage bus (500 kV) and lower voltage buses.

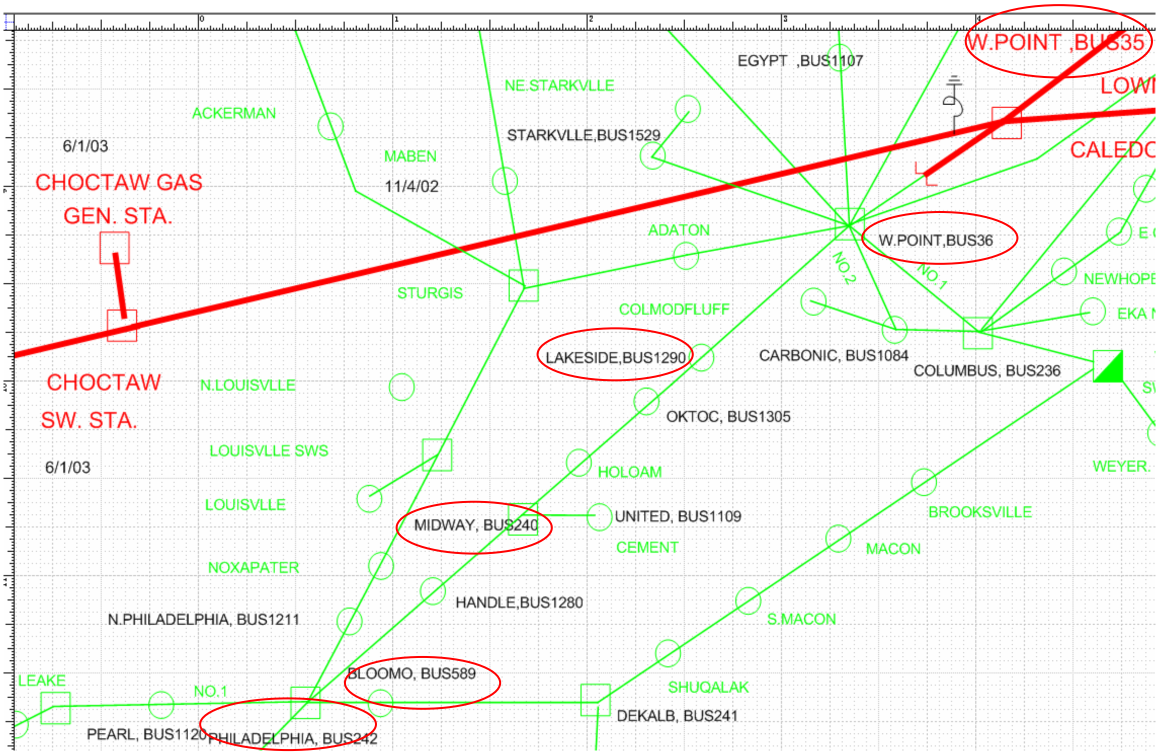


Figure 4.5 Simulation system model, the selected buses are in red ellipse

In the simulation, an event is introduced to the simulation system as a remote generator tripped in the system, so all the buses should experience frequency drop due to the imbalance between the power generation and the load, comparing the frequency response of the different buses can get the frequency shift along the distribution system.

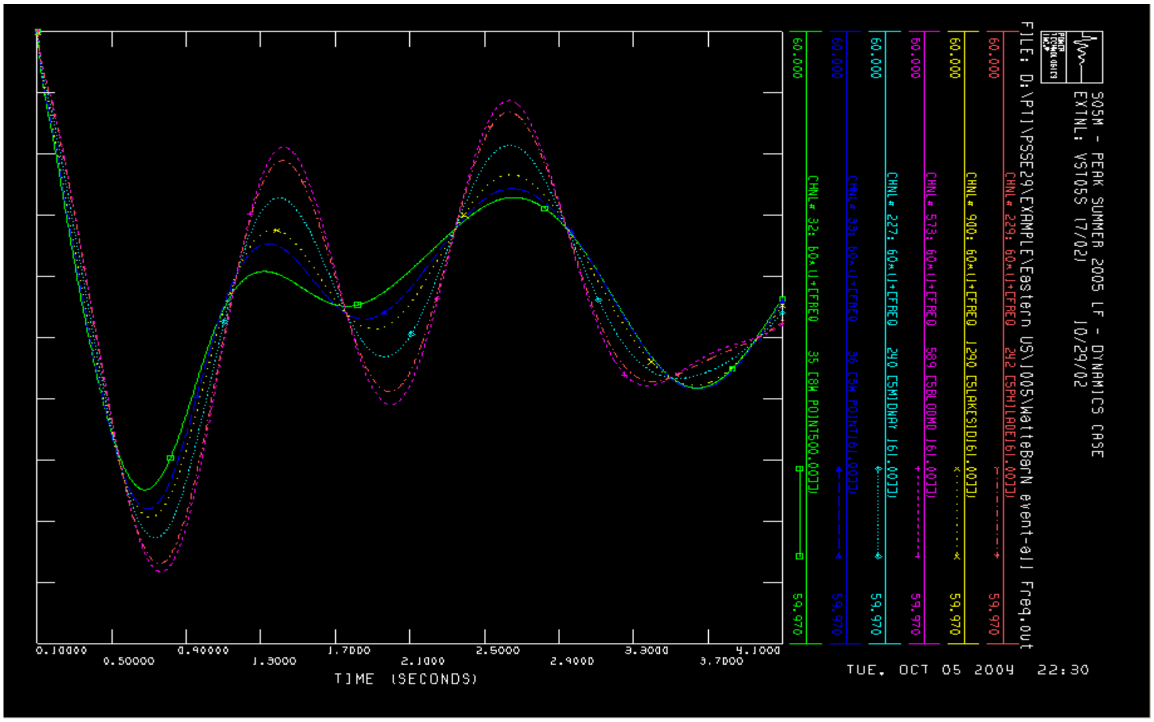



Figure 4.6 Frequency Response along Transmission Line

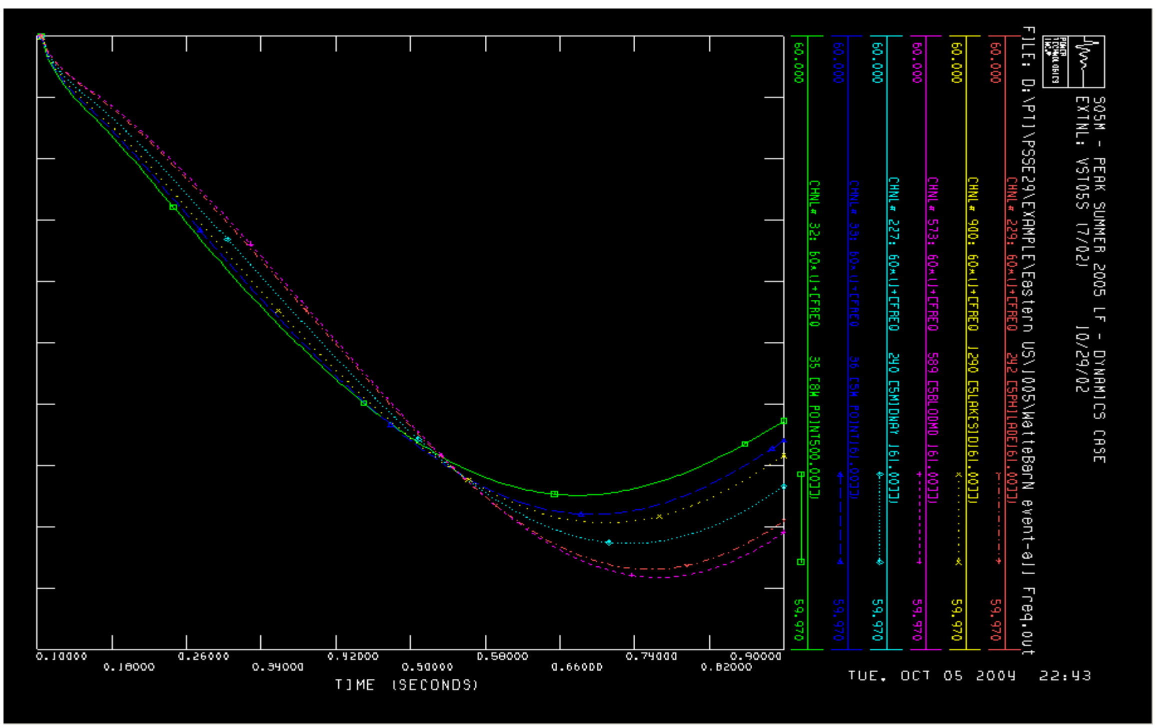



Figure 4.7 Detailed frequency response of the first swing

From the frequency response plots, the following analysis is derived:

- Frequency drop sequence: $35 \rightarrow 36 \rightarrow 1290 \rightarrow 240 \rightarrow 242 \rightarrow 589$ just follow the bus sequence in the transmission line.

- The maximum frequency excursions are different at different buses.
- Frequency curves across each other at the same point in every swing.
- The periods of oscillation of frequency wave at each bus are the same.

### 4.3.2 Field-measurement Data Comparison

The comparison is carried out between a FDR measuring at distribution load and a FDR measuring at a nearby substation's control room, also between a FDR measuring at distribution load and a nearby PMU at a 345 kV transmission line. From the result of comparison, we can conclude that measuring power frequency at distribution level outlets with good precision devices and proper signal processing tools is comparable to that at high voltage line using PMU. System's frequency dynamics can be well tracked by measuring at anywhere-accessible 110 V outlets.

For MF test, it was performed between Feb. 1, 2005 and Feb. 15, 2005. MF substation is located in Dixie Caverns, Virginia, which is about 50 miles northwest of Blacksburg, Virginia, where Virginia Tech is located. Based on the available information, Blacksburg is at its distribution supply line. In addition, it is the nearest high-voltage substation from Blacksburg. One FDR was placed in the control room of MF 345 kV substation. The detailed comparison is introduced in Shu-Jen Steven Tsai's Ph.D. dissertation. The comparisons provide strong evidence that the recordings from FDR with signal processing is the frequency of the electric transmission system using the nearby PMU measurement as the reference.

## 4.4 Statistical Analysis of Frequency Operation Pattern

The frequency descriptive statistics, such as average, median, standard deviation, maximum, and minimum can be calculated from recorded FDR raw data. Here the calculated statistics include normal condition and transient conditions (e.g. generation trip, line opening, load rejection, random event, etc) and based on the frequency data of each

FDR for each day. Each day is in the period from 00:00:00 to 24:00:00 EST (Eastern Standard Time).

From the comparison of short period, say 10 seconds, there is some minor difference between the frequencies from different units in the same interconnection as described in section 4.2. However, there is no difference between these units from the statistical view of the whole day; even there is a relatively large event happen in that day. So in this section, only one unit from each interconnection will be selected for the statistical analysis.

### 4.4.1 Average, Standard Deviation of the Raw Frequency Data

Between Apr. 1, 2004 and Apr. 30, 2005, the frequency statistics of FDR units in three US interconnected systems, namely, WECC, EUS, and ERCOT are calculated.

As we can see from the statistics, no matter how large the maximum frequency was or how small the minimum was in each day, the average frequency was close to the scheduled value: 60 Hz.  It is, however, interesting to notice that the standard deviation (STD) of frequency for each day stays in the same level for each system. For EUS, the STD is about 0.015, for WECC, it is about 0.013, and for ERCOT it ranges from about 0.02 to 0.04. Standard deviation can be used as a measure of the dispersion or variation in a distribution. In other words, it is a measure of how much the data in a certain collection are scattered around the average (mean). From the standard deviation value, the frequency in ERCOT is varying at a larger range than that of EUS and WECC. One reason for having different STD, from power system's point of view, could be that different interconnections have different capacity. According to the frequency response analysis, the frequency of the system with smaller capacity will be more unstable. This means with the same amount of deviation of power balance, the smaller system will have larger frequency variation. This also means if all these interconnections experience the same amount of frequency variation, the system with smaller capacity will need smaller amount of power unbalance.

### 4.4.2 Frequency Integral Analysis in EUS Interconnection

In order to analyze the frequency operation pattern, the integral of the deviation of raw frequency data and nominal system frequency (60 Hz) is introduced. This analysis is trying to use this statistical method to find out how frequency is controlled everyday, and the accumulative effect of frequency deviation. With this method, it is very clear to find out in a day, what time the frequency is above 60 Hz and what time the frequency is below 60 Hz. Here we use four units in EUS, and these units are: NY, UMR, ARI, VT; the starting time is 9:30:00 EST, Feb. 13, 2004, and the calculation window is three hours. In the following figures, Y Axis: $S(t)=\int_0^t (f-f_0)dt$ , $f_0=60$. From these figures, we can see that the frequency at each unit has the same trend because they are in the same interconnection, and so the integral of the deviation is the same. During this period, the main trend of the frequency is above nominal 60 Hz, only some short period when the curve goes down the frequency is operated below 60 Hz.

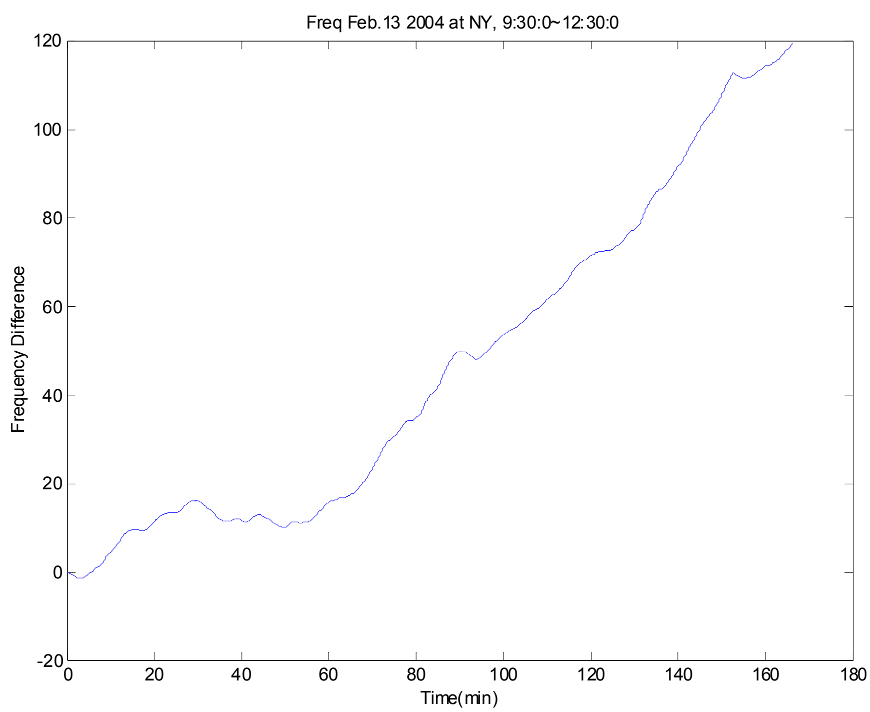



Figure 4.8 Integral of Frequency Deviation of NY unit

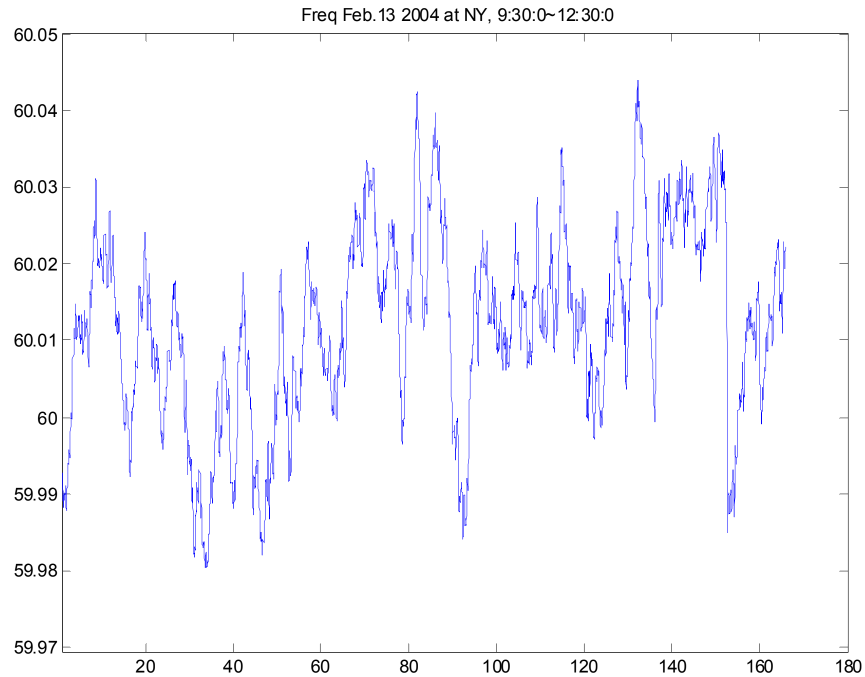



Figure 4.9 Raw Frequency Data of NY unit

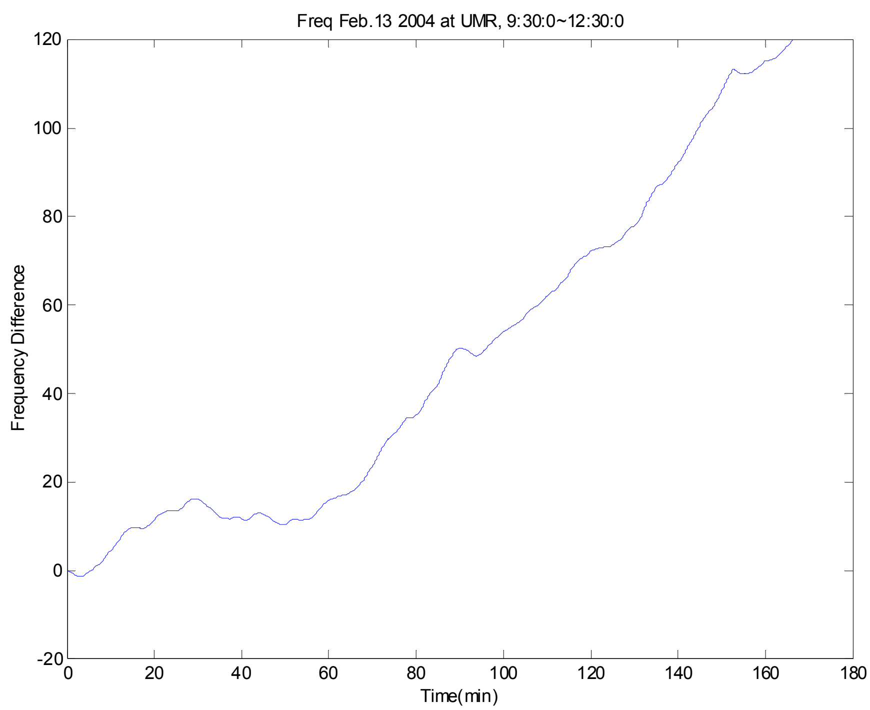



Figure 4.10 Integral of Frequency Deviation of UMR unit

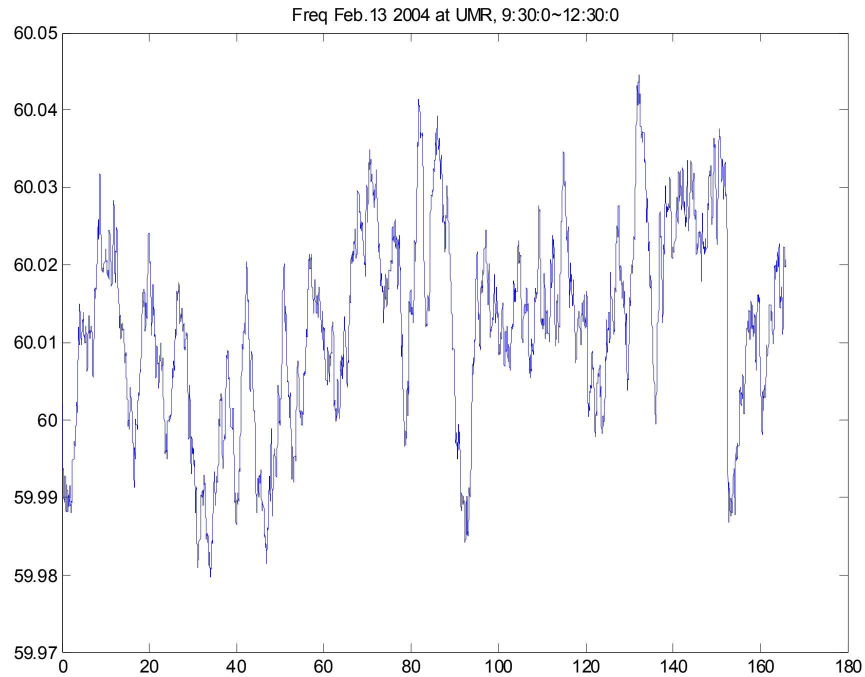



Figure 4.11 Raw Frequency Data of UMR unit

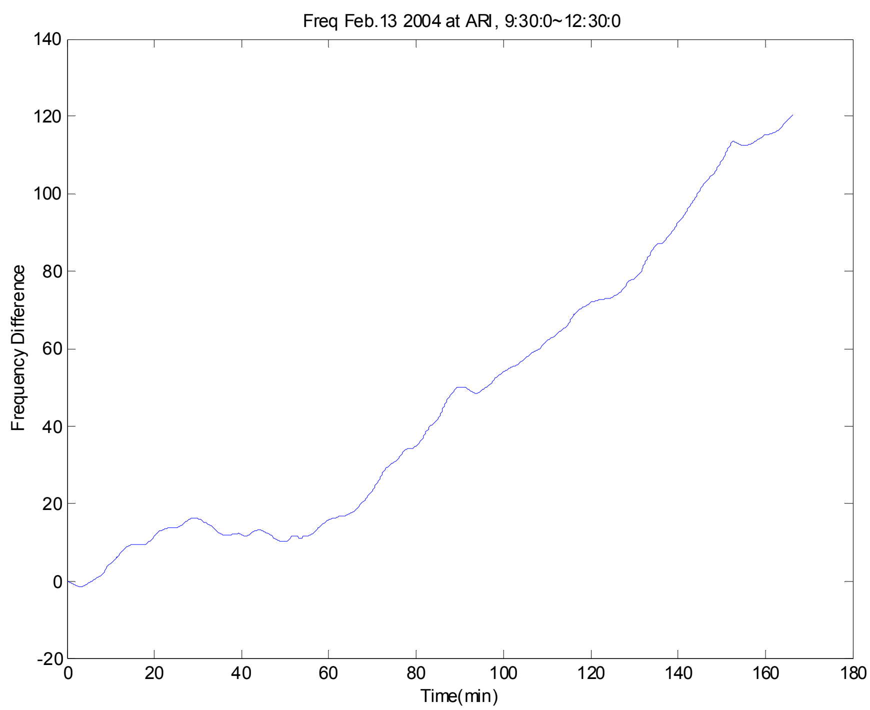



Figure 4.12 Integral of Frequency Deviation of ARI unit

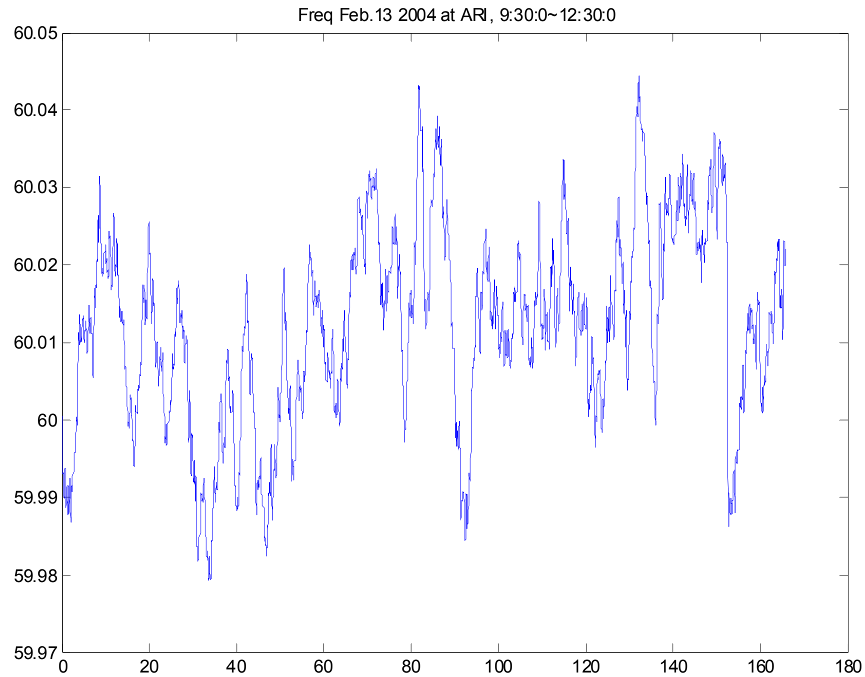



Figure 4.13 Raw Frequency Data of ARI unit

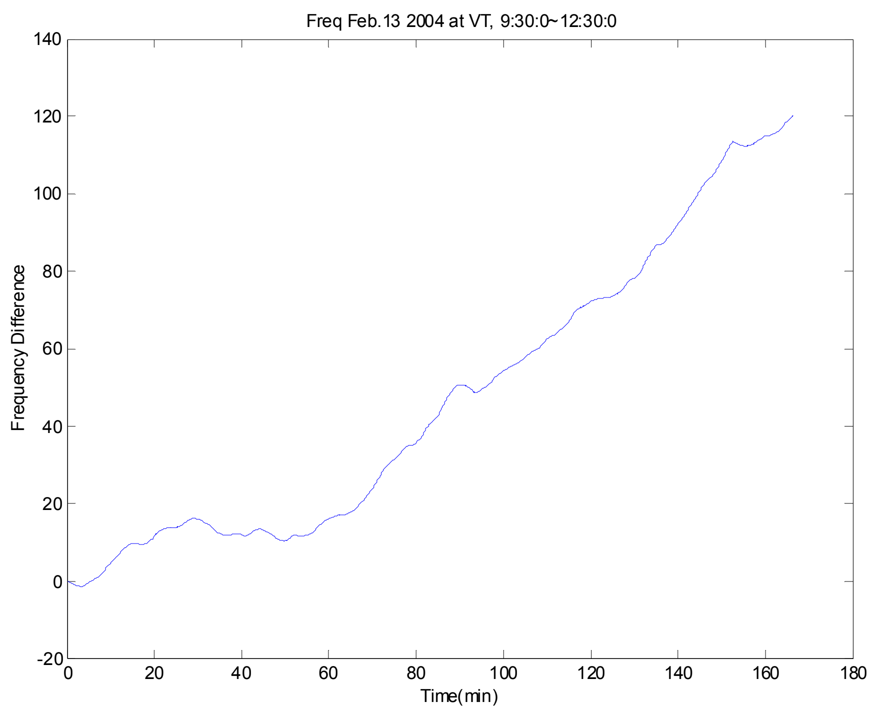



Figure 4.14 Integral of Frequency Deviation of VT unit

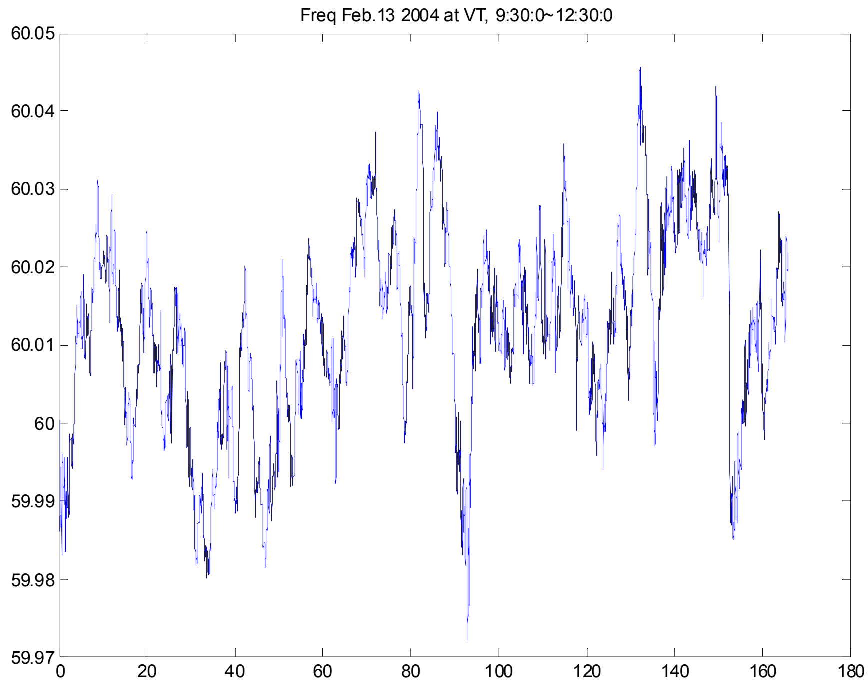



Figure 4.15 Raw Frequency Data of VT unit

### 4.4.3 Long-term Frequency Analysis

In the previous section, the integral of different of the same time is analyzed and we can conclude that the integral and frequency pattern is the same in the same interconnection. Hence, in this section, in order to analyze the long term pattern, only one unit is selected to calculate the integral of frequency deviation in a daily mode to get the daily accumulative effect of the frequency pattern. In the following figures, the frequency data from ARI unit is analyzed. The Y-axis is the integral of frequency difference, and X-axis is time starting from midnight. The figure in the left side is the integral and right side is raw frequency data. Y Axis: $S(t)=\int_0^t (f-f_0)dt$ , $f_0=60$.

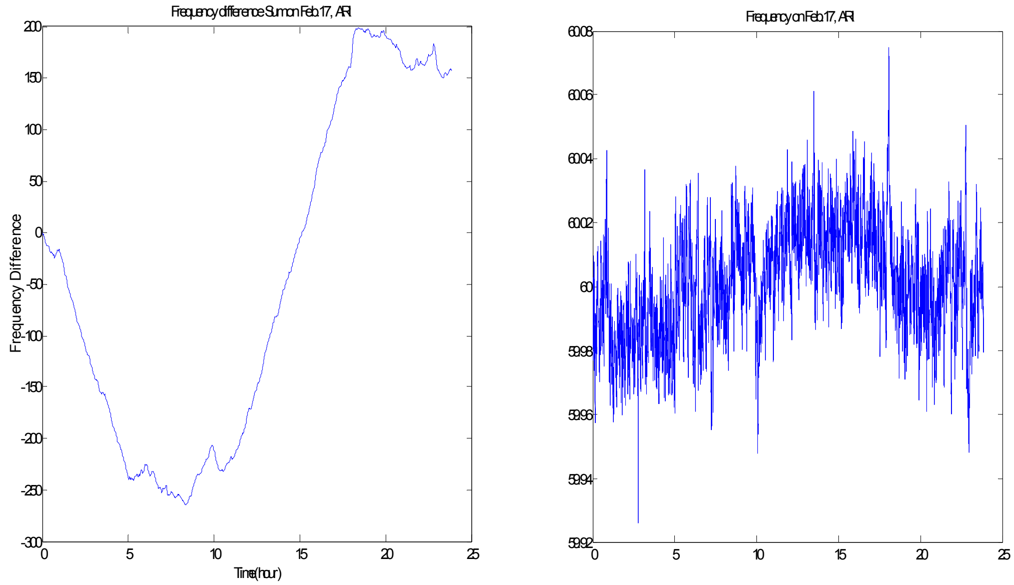



Figure 4.16 Integral of Frequency deviation and raw data on Feb.17, 2004

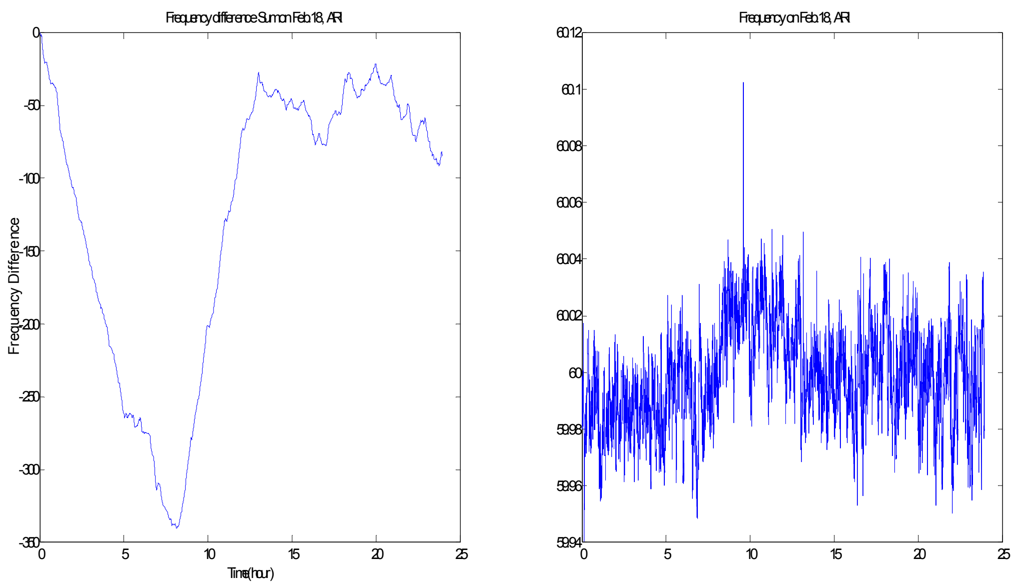



Figure 4.17 Integral of Frequency deviation and raw data on Feb.18, 2004

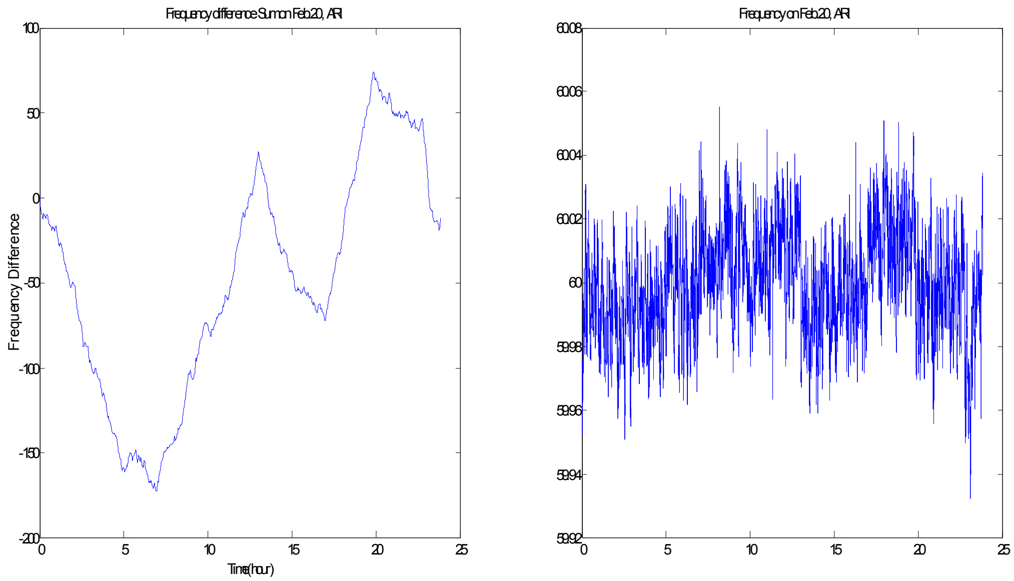



Figure 4.18 Integral of Frequency deviation and raw data on Feb.20, 2004

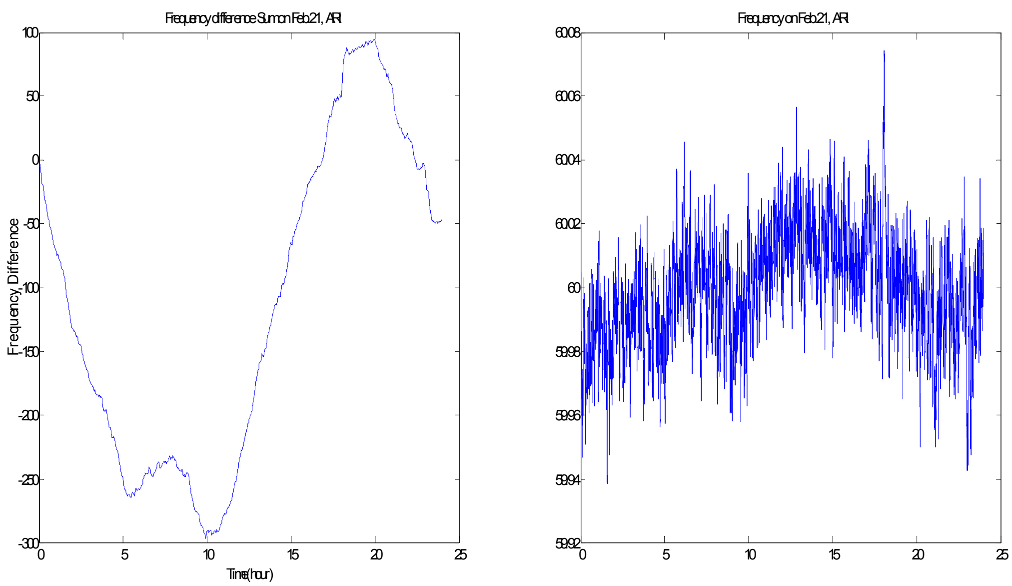



Figure 4.19 Integral of Frequency deviation and raw data on Feb.21, 2004

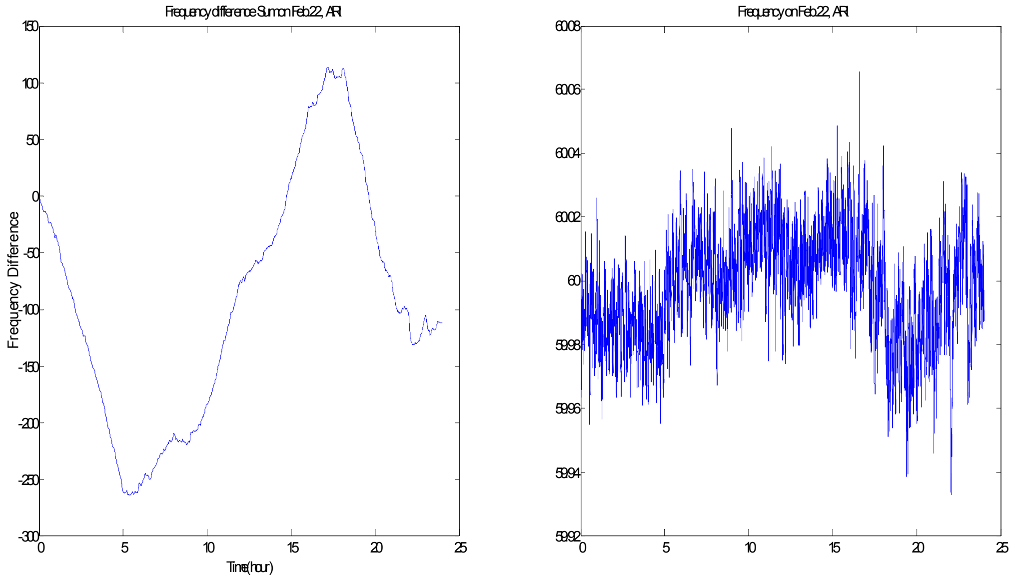



Figure 4.20 Integral of Frequency deviation and raw data on Feb.22, 2004

From the figures show above, we can find out that there is some regulation in operate the power system frequency. The frequency is always below 60 Hz from 0 to 6 o'clock, then increases and oscillates around 60 Hz but most is above 60 Hz from 6 to 18 o'clock, after that the frequency declines again. This series is analyzed for the winter season and the following figures show the frequency in summer season.

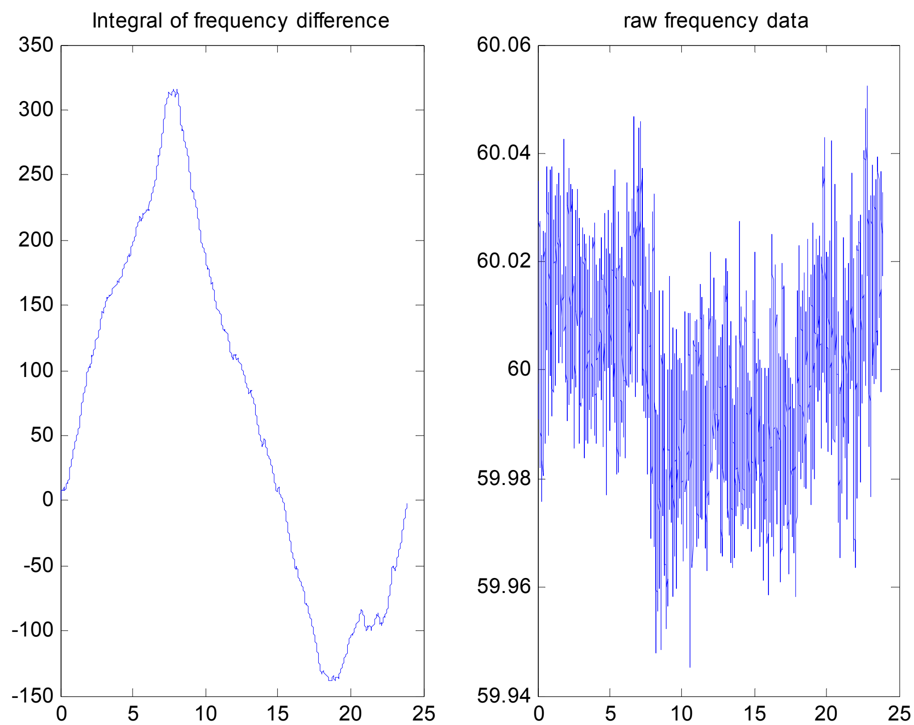



Figure 4.21 Integral of Frequency deviation and raw data on Aug. 1, 2004

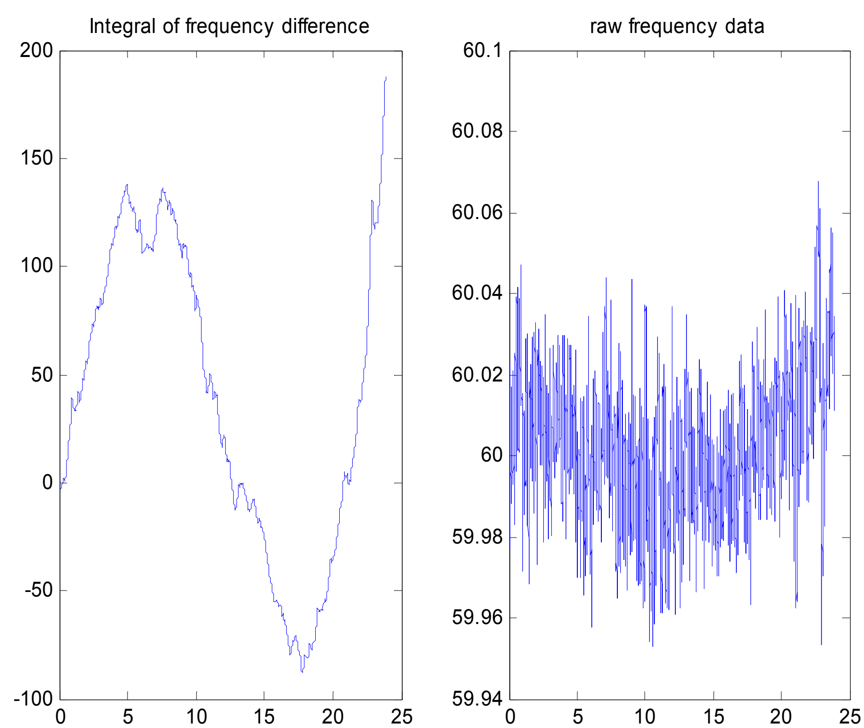



Figure 4.22 Integral of Frequency deviation and raw data on Aug. 2, 2004

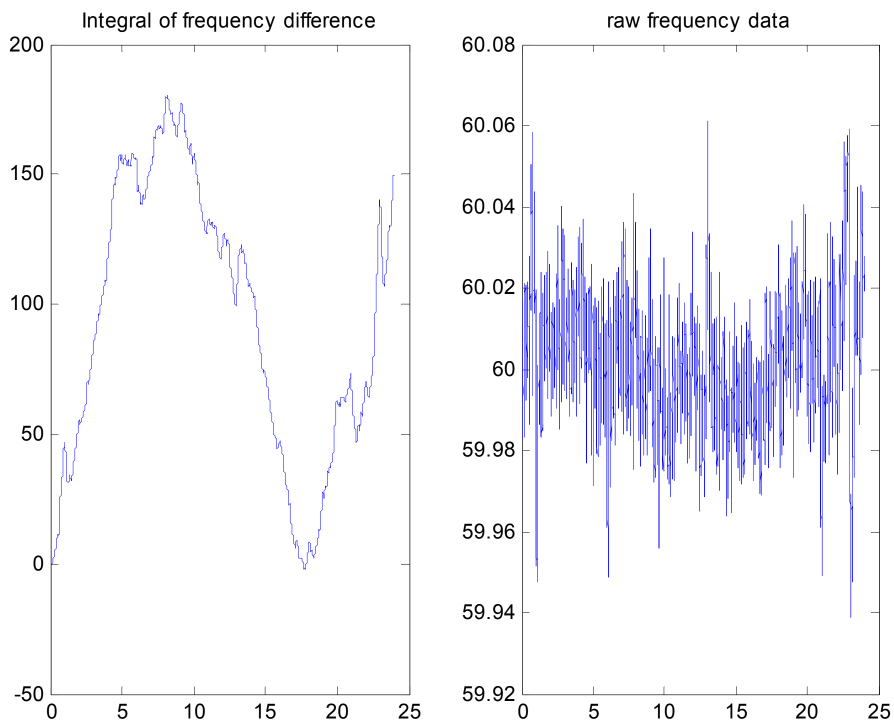



Figure 4.23 Integral of Frequency deviation and raw data on Aug. 3, 2004

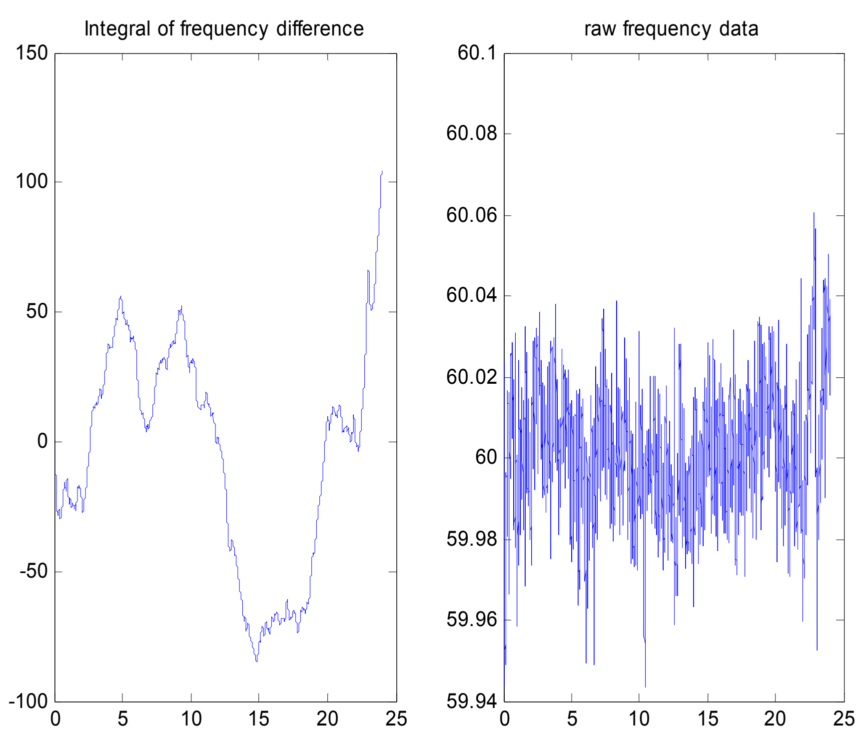



Figure 4.24 Integral of Frequency deviation and raw data on Aug. 4, 2004

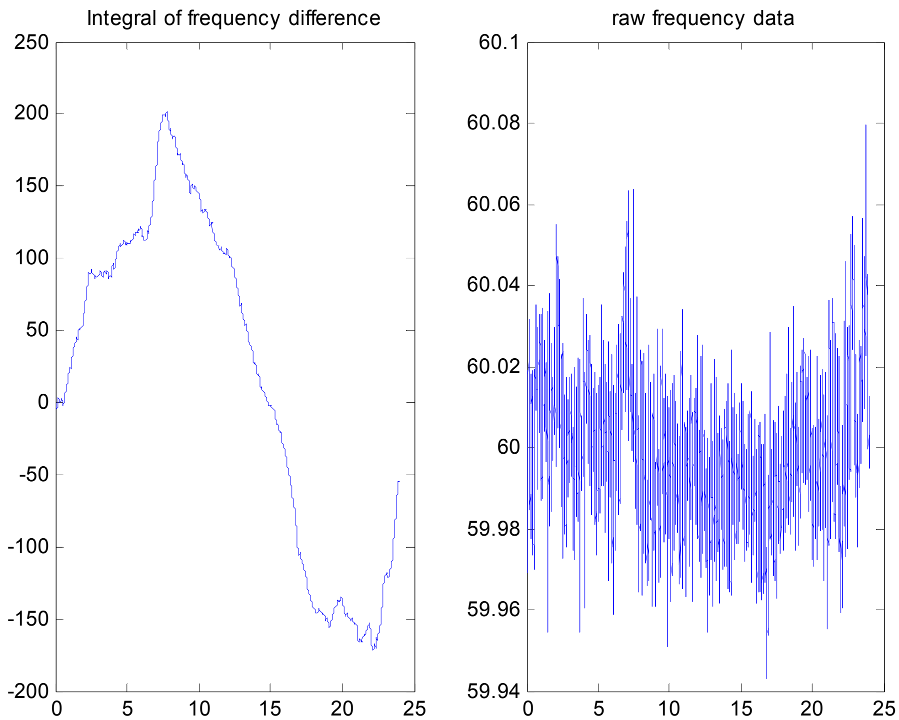



Figure 4.25 Integral of Frequency deviation and raw data on Aug. 8, 2004

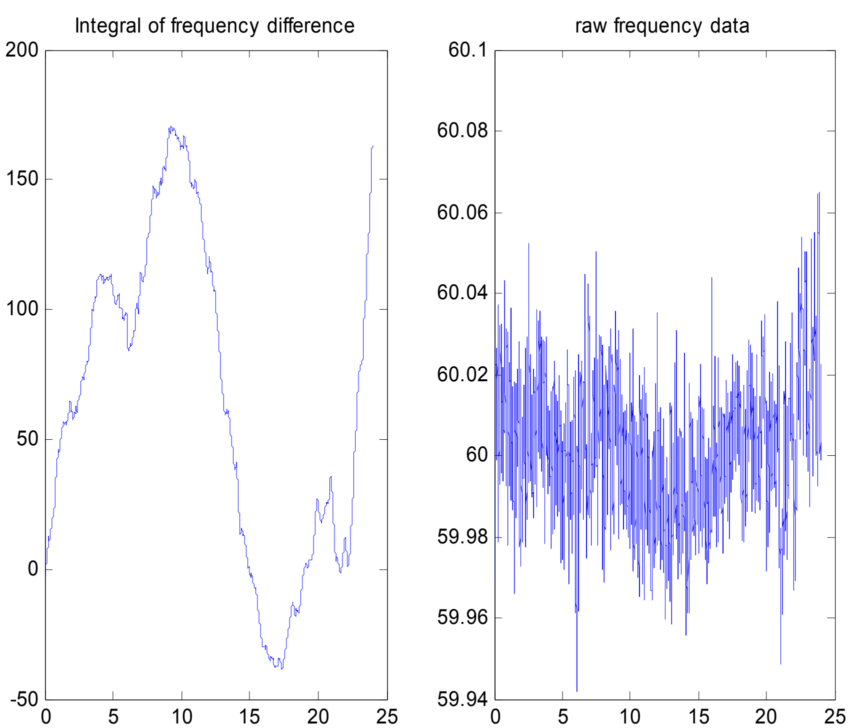



Figure 4.26 Integral of Frequency deviation and raw data on Aug. 9, 2004

From the above figures, we can find out that there is some regulation in operate the power system frequency. The frequency is always above 60Hz from 0 to about 8 o'clock, then decreases and oscillates around 60Hz but most is below 60Hz from 8 to 18 o'clock, after that the frequency stay above 60Hz again. Here, some statistical data of the frequency are calculated and listed in the Table 4.1.

Table 4.1 Statistical Frequency Result of ARI Unit

| Date | Frequency Mean (Hz) | Frequency STD |
|---|---|---|
| Aug. 1 | 60-2.2365e-5 | 0.0164 |
| Aug. 2 | 60+0.0022 | 0.0161 |
| Aug. 3 | 60+0.0017 | 0.0152 |
| Aug. 4 | 60+0.0012 | 0.0144 |
| Aug. 8 | 60- 0.00063388 | 0.0161 |
| Aug. 9 | 60+0.0019 | 0.0156 |
| Aug. 11 | 60-0.0012445 | 0.0135 |
| Aug. 12 | 60-0.0029255 | 0.0163 |
| Aug. 13 | 60+0.00203 | 0.01258 |
| Aug. 14 | 60+3.5854e-5 | 0.01335 |

From these statistical data, the frequency regulation in weekend is better than in weekday, since the mean of frequency is much closer to 60Hz (such as on Aug. 1, Aug. 8 and Aug. 14); while the standard deviation of the frequency varies in a range.

From calculation, the frequency quality in WSCC is better than that in EUS. Because the frequency of WSCC is in the range of ±0.02Hz and oscillates around 60Hz at most time, while the frequency of EUS system always stay below 60Hz for a very long period and then stay above 60Hz for a period, and its range almost is double size of the WSCC range.

## 4.5 Regional Frequency Oscillation Analysis

From the observation result of the FNET system, there is some frequency consist of some local component, which is the occurrence of oscillations, indicating the possibility of potential system instability. When such kind of event happens, oscillations can be detected in all the measured variables of the power system: frequency, voltage and so on. Sometimes the event can last for very long time. In some area, such as New England area, there is some oscillation happened occasionally, and the cause of the oscillation is unknown. In the area of Calvin, some oscillation is revealed, and the figure shows the outlook of this kind of oscillation.

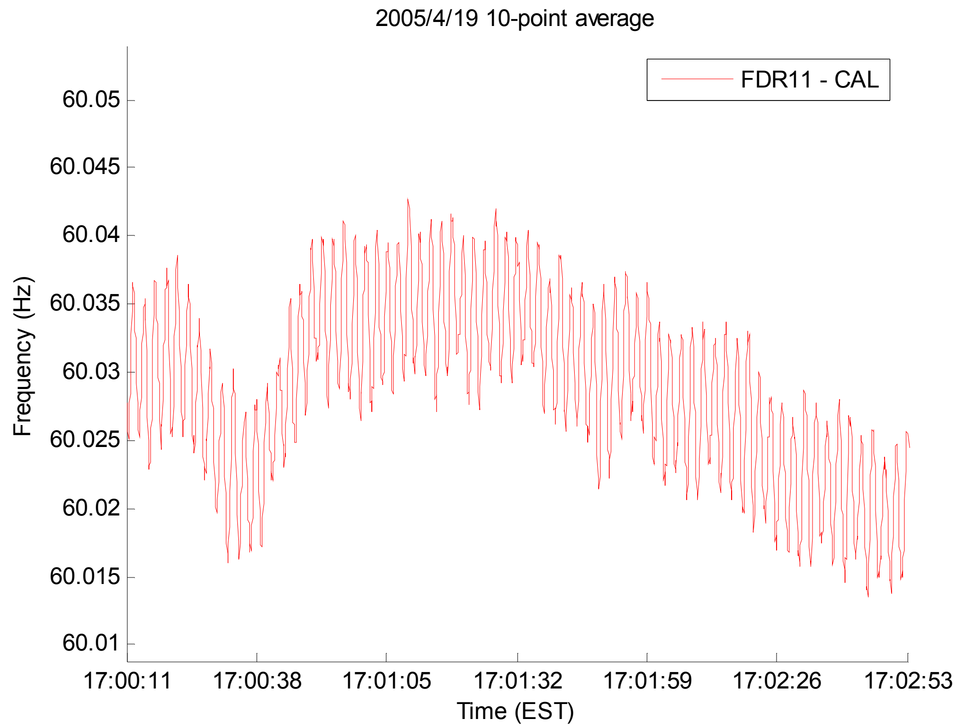



Figure 4.27 Frequency Oscillation of Calvin Unit on Apr. 19, 2005

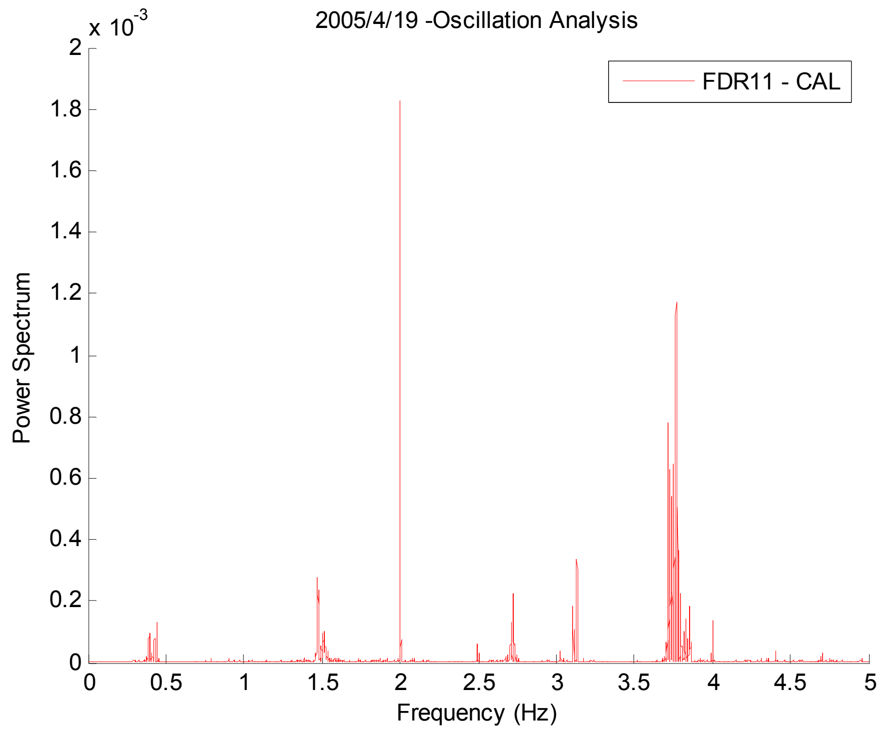



Figure 4.28 Spectrum Analysis of Frequency Oscillation of Calvin Unit on Apr. 19, 2005

In today's practical power systems, the oscillation can be generally classified in four modes: local modes (machine-system modes), inter-area modes, control modes, torsional modes [56]. From FDR data, we are able to observe electromechanical oscillation modes, namely, local modes, and inter-area modes. Local modes are typically in the 1~3 Hz range between a remotely located power station and the rest of the system; and inter-area oscillations are in the range of less than 1 Hz [57]. From our experiences, these oscillation modes can only happen occasionally and the time-series characteristics are not as obvious as those characteristics in generation drop, line opening, or load rejection.

In order to understand the characteristic of the oscillation, some preliminary analysis is employed in Matlab. The following solution is to use the spectrum analysis of the oscillation to get the fundamental frequency component of oscillation. The 10-point average frequency is first calculated to get the smoothed frequency wave, and represent the frequency in absence of oscillation. Then the difference of raw frequency and average frequency is calculated to get the deviation of oscillation. With this deviation, the power spectrum can be used to reveal the fundamental oscillation frequency of the wave. In the following figures, the spectrum analysis method is applied to the frequency data of units in EUS and the oscillation frequency is showed in the figures.

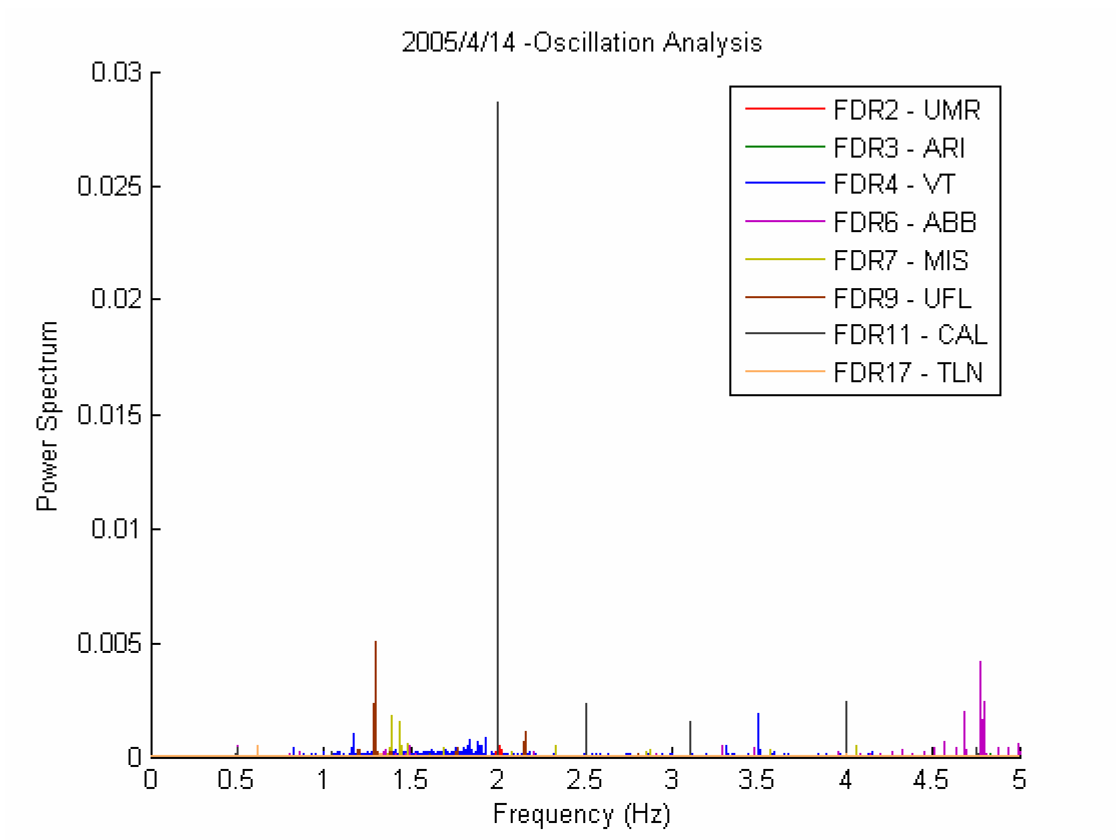



Figure 4.29 Spectrum Analysis of Frequency Oscillation in EUS on Apr. 14, 2005

Please refer to the Appendix for the plot of oscillation analysis result. From the plot, it is very clear that there is a 2Hz oscillation on the frequency wave in the Calvin area for the observed period. However, for the other units, there is some uncertain oscillation in some particular day, such as for UFL unit, there is an oscillation around 1.3Hz on Apr. 8 ~ Apr. 10. The source of these oscillations is still under investigated. Here the result shows that the frequency data from FNET is a very promising data source for the future research work on oscillation mode analysis.

## 4.6 Summary

With the implementation of the first phase of FNET system, the raw field-measured frequency is investigated in this chapter. General system operating frequency is examined and the characteristics of frequency deviation of the EUS, WECC and ERCOT are given. The propagation of frequency in distribution system is analyzed and the result shows the 110V outlet frequency can represent the system frequency. Some statistical analysis of frequency is given and long-term frequency pattern is investigated. Standard deviation reveals a measure of the dispersion or variation in a distribution. The daily analysis of frequency shows the operation pattern of the EUS. In addition to observing transient states of the system, we can also use the FNET data to observe system's frequency oscillation and one example case is provided.

# Chapter 5 Disturbance Analysis Based on the Frequency Information from FNET

## 5.1 Introduction

Power systems are vital links that achieve the essential continuity of service from the generating plants to the end users. From the point of economics, social impact, and especially homeland security, the importance of fast major fault detection/location in the power systems is increasing. Automatic event identification in power systems is essential to both normal operation and emergency control. During normal operation, operators need aids from tools to analyze disturbances, and to derive other useful information. In emergencies, they even more rely on tools to assess system security conditions, and to determine control options.

Accurate and fast identification of an event could help achieve early alerting; clear understanding of the ongoing disturbance, and ultimately triggering early corrective emergency controls [58]. The synchronized high-resolution phasors provided by Phasor Measurement Units have proven capable of revealing system dynamic operations [59][64]. Frequency is the most important signal for event identification in this research. The task of disturbance identification and analysis has the following closely related objectives:

- Trigger: design event trigger algorithm to detect the abnormal frequency change;
- Confirmer: use a certain number of units to confirm the detected abnormal frequency is a system behavior, and record the time difference of each unit experiences the change;
- Locater: use the time difference and the change sequence information as input to get the location of the source of this abnormal frequency change;
- Estimator: design algorithm to calculate the power change during this disturbance, Generation equation, coefficient training by current events.

Figure 5.1 describes the relation and sequence of these objectives. From this point of view, when frequency data streams into the server, the program first directs these data to the particular memory for each unit according to the unit number. Then the data will be filled into trigger program to determine whether the frequency change reach the setting threshold. If it falls into trigger, the program will go to confirmer stage to make sure it is a system-range frequency change and then go to localization program to estimate the location of the source of this frequency change, at the same time, the estimation of generation change during the disturbance is achieved. In each step, if the flow does not meet the setting criteria, it will go back to the first step.

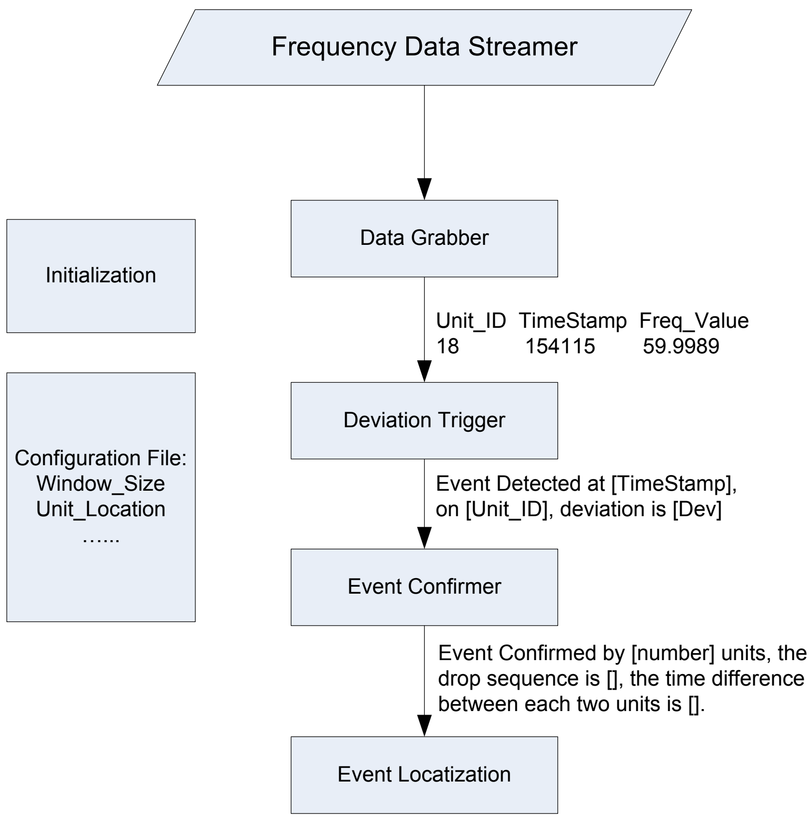



Figure 5.1 Flow chart of disturbance detect and analysis

For the trigger, threshold of the deviation of frequency during a certain period is addressed. The thresholds of different interconnections are different, because each interconnection has its own frequency characteristic. The threshold can be trained by the known cases with the learning algorithm [65][67].

For the localization of disturbance event, time difference of arrival (TDOA) method [68]-[71] is introduced as the preliminary step of the location area determination, and electrical network model method is the second step to get the real location in very short time after the disturbance happens.

For the estimator of the changed power during the disturbance, learning algorithm of artificial neuron [72] is introduced to train the coefficient of the empirical equation, which is built on the frequency response characteristics.

## 5.2 Trigger Design to Detect Disturbance in Power Grid

### 5.2.1 Principle of the Trigger Idea

The first issue for the disturbance analysis is to detect the fault event happened in the power system, and then to get the detailed frequency information during the disturbance period.

In the power system, if there is a generator or part of the generation of a generator tripped, the residual generating capacity no longer matches the connected system load and this will cause the system frequency to experience a sudden drop. The frequency change is the difference of frequencies before and after a disturbance, and the frequency change is an indicator of how much generation was removed or added in the interconnected system. So the frequency change can be used as a detector of event in the system. In general, tripping a load in the system should increase the system frequency. Because individual loads are much smaller than the generating units, and frequency changes are usually so small, so that the event practically cannot be detected. That is to say, the frequency change can reflect (indicate) the system generation balance change, so when there is a sudden decline of the system frequency, there must be a change of the generation balance. This can be used to find out system disturbance cause by generation loss.

Finding the sudden frequency drop in the continuous frequency data is the way to get the fault event detailed time from the large amount of the recorded data. Especially, if there is an online algorithm to detect the sudden frequency drop in FNET system, the generation trip event can be found at a very early time. Firstly, an offline algorithm is needed to find out the event in recorded frequency data in the database, and then apply this algorithm to the real-time database to set an alarm trigger for system fault event.

The trigger is set with a threshold of average frequency deviation in a certain period. Normally the frequency supposes to vibrate slightly around 60 Hz and do not change rapidly because of the mechanical characteristics. Therefore, the average frequency of a certain period can be a good estimation of the frequency in the near future. Then the deviation between the real frequency and the estimated frequency can illustrate the veracity of the estimation. When the deviation reach the setting threshold, the system deviates from steady status and some disturbance happens.

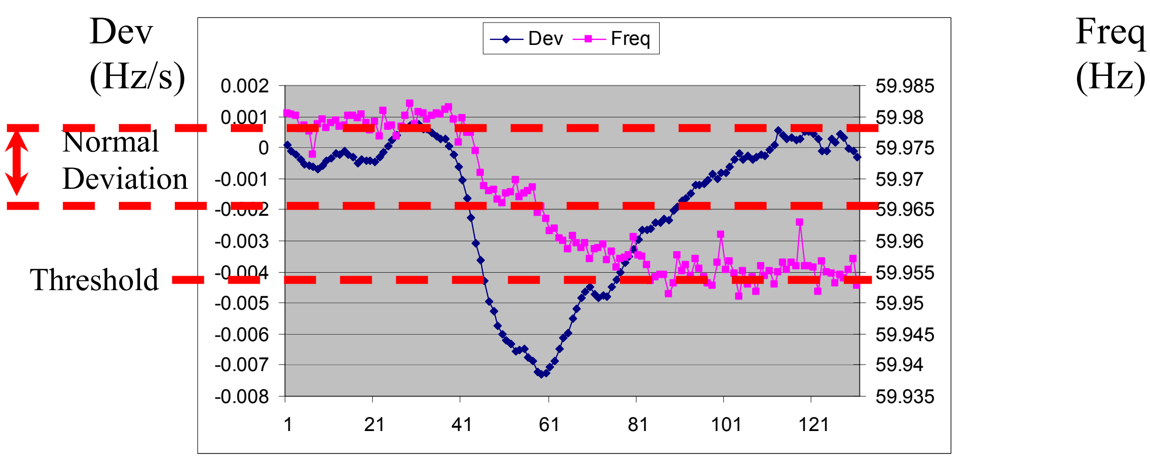



Figure 5.2 Illustration of the Trigger Design

Mathematically speaking, the trigger idea can be explained in this way. For the nominal frequency behavior, the frequency can be presented as $f(t) = 60Hz$, and if the system is running in the theoretic steady mode. While for the real frequency in the system, the frequency will vary in the adjacent range of 60Hz, and the average $f(t) = AVERAGE(f)$ of the window size can express the frequency, so the next frequency point suppose to behavior as the average frequency before, use moving average with window size of 4 seconds, the deviation between average frequency can be calculated. If the system is running in the steady status, the deviation supposes to fall in a certain operating range, and this range can vary in different interconnection. If the deviation is out of the range, the trigger is active.

The average method can remove the spike effect to the calculation result to eliminate the local one-point spike, which will confuse the trigger program and send wrong alarm message. Most of this kind of frequency change is caused by generator trip or load lost in the power grid. Using this method, the spikes which caused by some uncertain local switch or noise will be filtered.

Another issue for the trigger design is the threshold. In order to detect the abnormal frequency change, the threshold setting is very important because improper threshold will either miss some disturbance or alarm too often by the normal frequency deviation.

### 5.2.2 Offline Trigger Algorithm Design

With the principle of the trigger, a Matlab based program is designed to detect the frequency drop event in the stored historical frequency data. For a long period of historical frequency data, such as one day of frequency data, that will be 864000 frequency data points for one unit. 5 seconds pre-event data (50 points) and 5 seconds post-event data (50 points) are used to detect the generation tripped fault event. In the offline trigger design, the calculation window is 5 second, and the threshold of deviation will be set according to the calculation window.

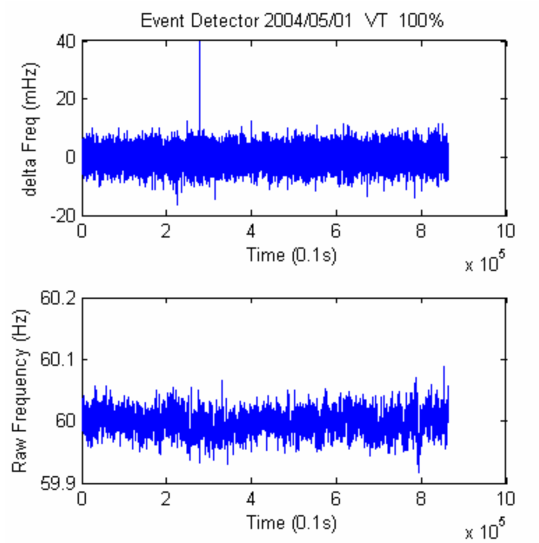



Figure 5.3 Frequency Event Detection Algorithm Sample Case on May 5, 2004

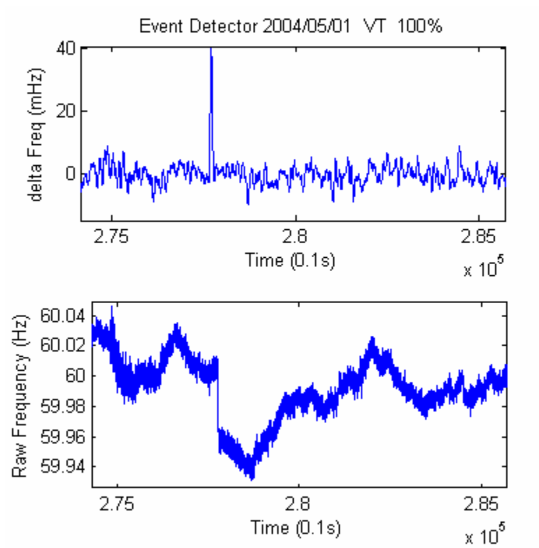



Figure 5.4 Detailed Observation of the Sample Case on May 5, 2004

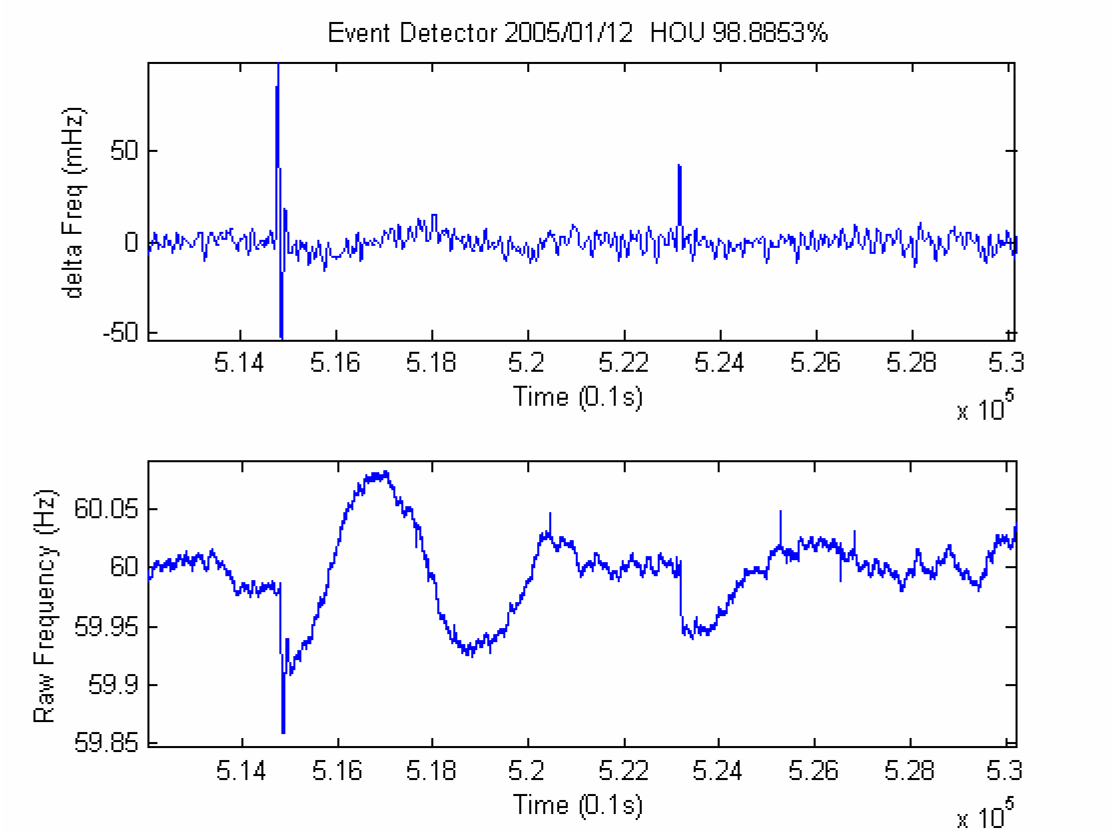



Figure 5.5 Detected Event in ERCOT on Jan.12, 2005

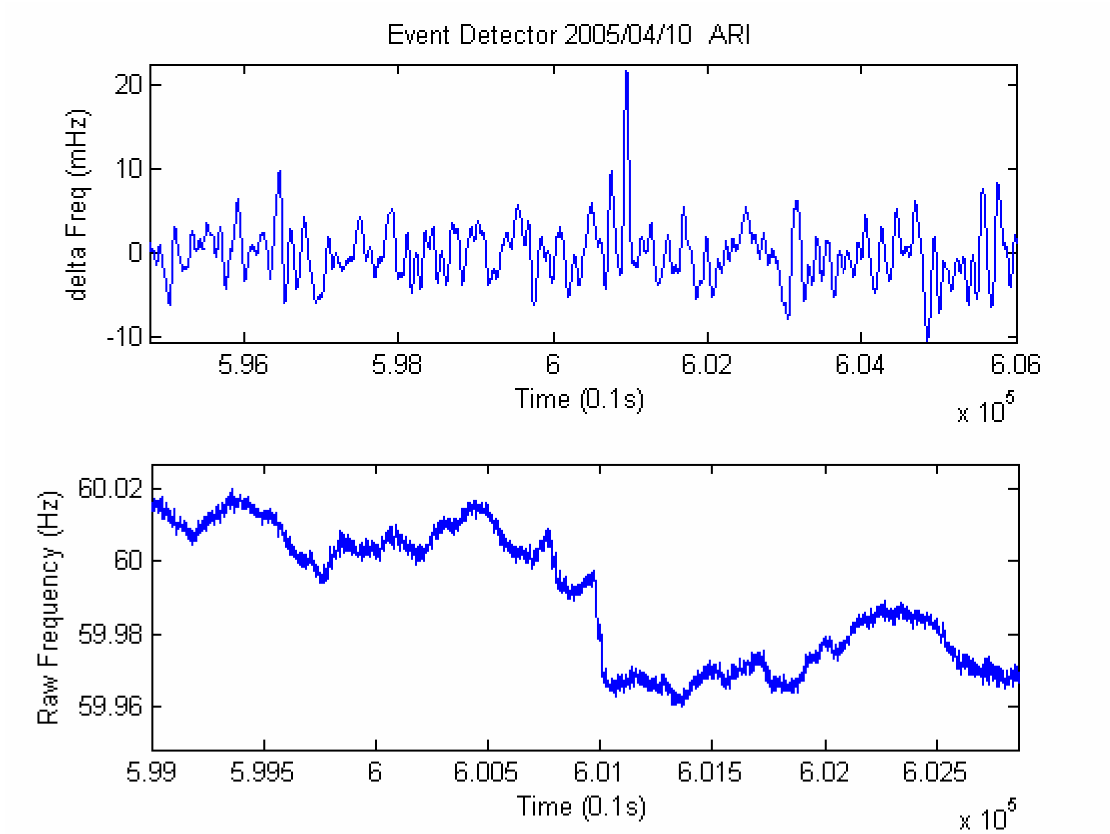



Figure 5.6 Detected Event in EUS with ARI unit on Apr. 4, 2005

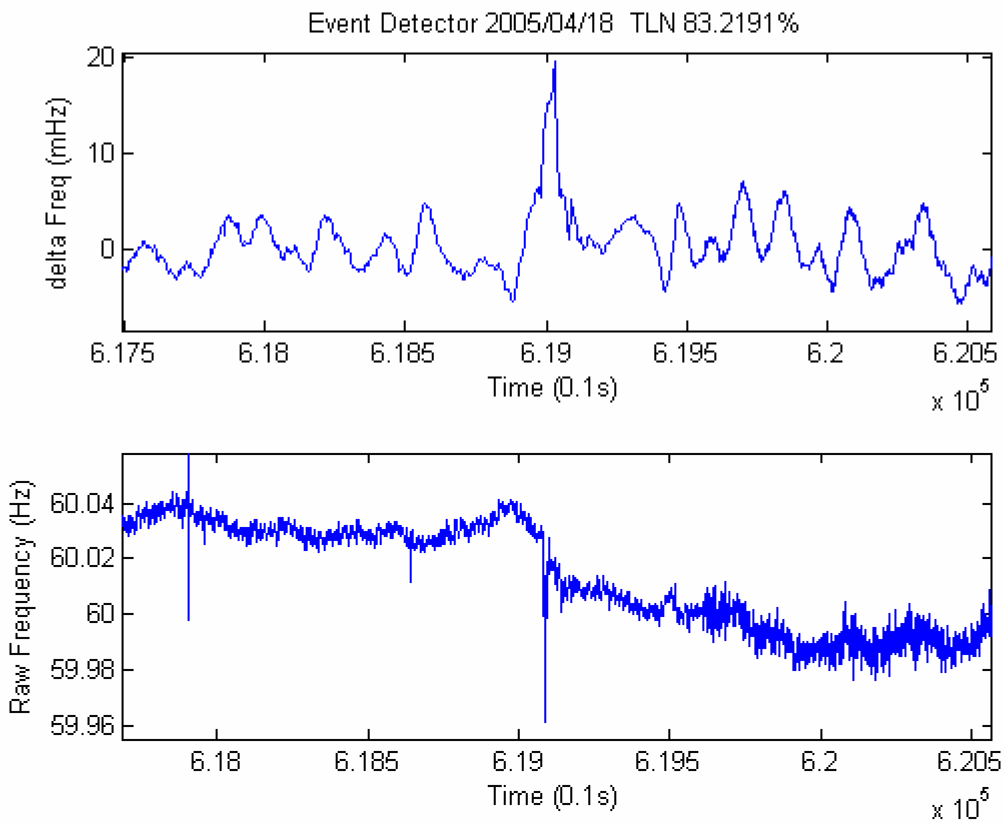



Figure 5.7 Detected Local Event in EUS with TLN unit on Apr. 18, 2005

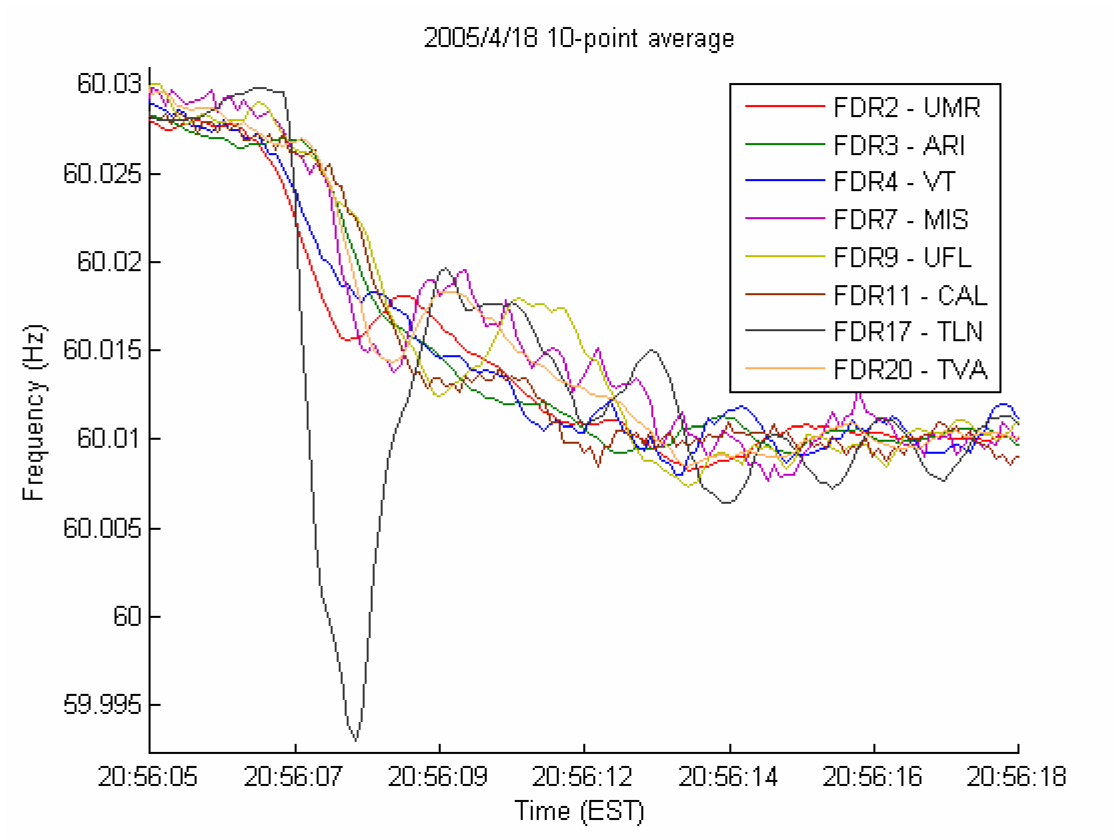



Figure 5.8 Frequency Plot of all Units in TLN Detected Event on Apr. 4, 2005

With this offline program, almost all the generation tripping events happened in the system can be detected from the FNET frequency data recorded in the database.

### 5.2.3 Online Trigger Prototype

Online trigger program can be easily employed with the same algorithm. When the data stream into the server, a shared memory can be used to store the data of needed period. Then the trigger will find the abnormal frequency deviation and send out the alarm message.

Some modification should be made of online trigger program. The data points used for moving average should be changed because the offline trigger algorithm uses 5 seconds as calculation window and that implies there is a 5-second delay. In order to keep the fast response of the real-time program, the calculation window should be changed to two-second or even shorter to avoid time delay. The threshold is defined as the frequency deviation in unit period; hence, it should be changed due to this difference.

### 5.2.4 Confirmer of Event

Some events only reflect the local power change and the effect does not propagate, refer to the following MIS event plot. It is very clear that the power balance lost in the area where the unit of MIS located, and the local frequency fluctuated for several minutes, and then some generation lost to make the frequency decline to around 59.9Hz and with some control device response, the frequency went back and resynchronized with the interconnection.

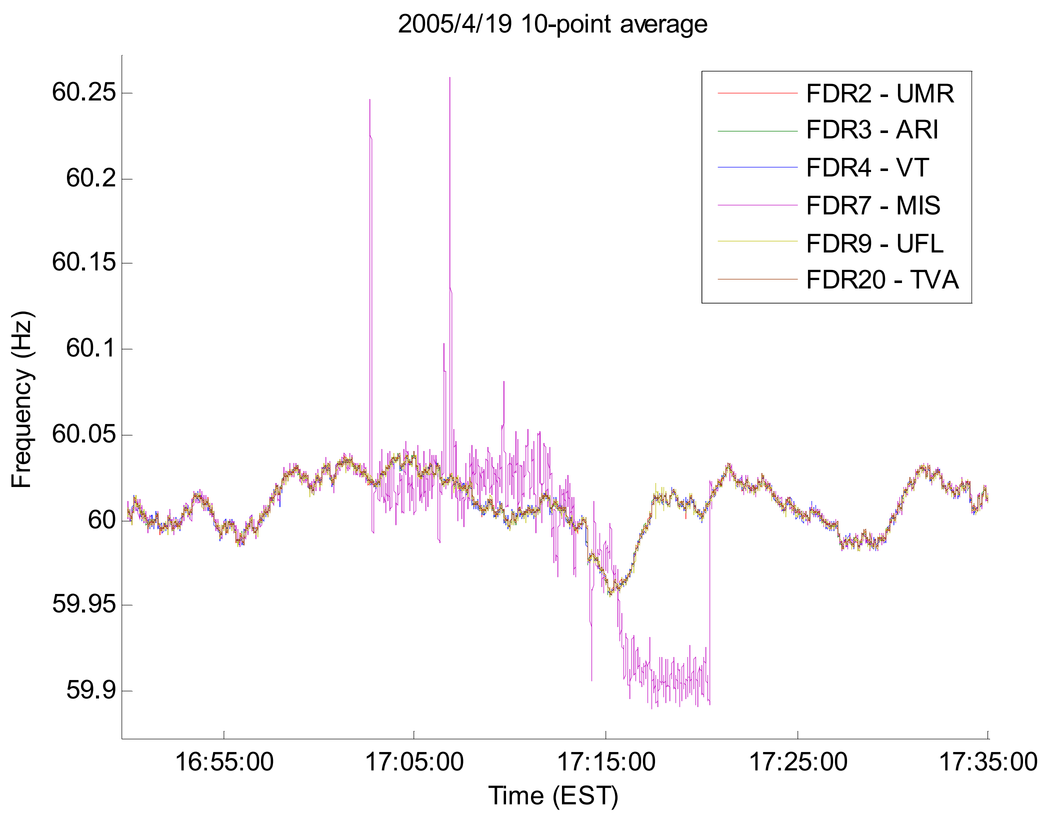



Figure 5.9 Local Frequency Fluctuation near MISS Area on Apr. 19, 2005

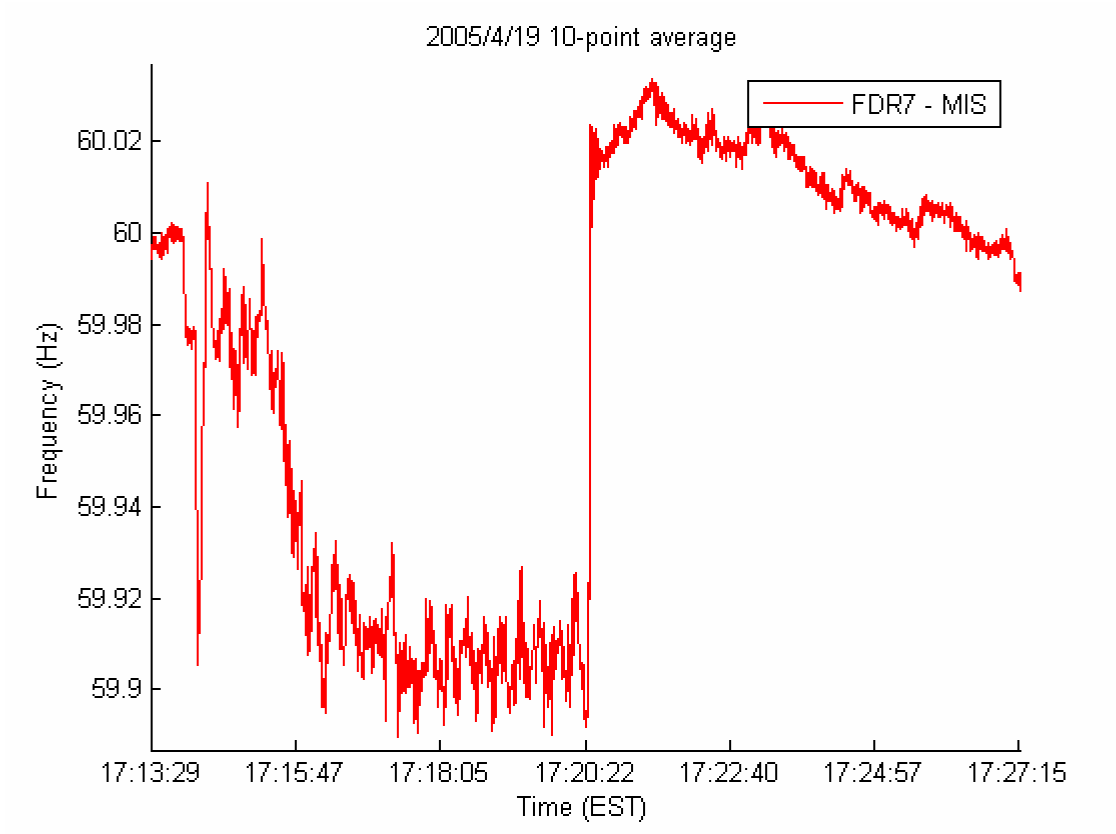



Figure 5.10 Frequency Recovery after Disturbance in MISS event

While most of frequency fluctuation event can be detected by the units all around the power grid, and this kind of events can be named as system level frequency fluctuation.

So for the online real-time trigger program, the event can be divided into two catalogs, one is the local disturbance, which means only one unit has responses for the event; another one is the system level disturbance that means more than one unit response in a very short time period (2~4 seconds).

The idea of confirmer is to set a vector to store the trigger information. when one unit active the trigger, the time stamp and the deviation of this event will be stored in the vector, and then if there is some other unit also detects this event in the following several seconds, the event is confirmed. In FNET system, the FDR units are located geographically and electrically dispersed, so if there are two or more units detect the event simultaneously, the confirmer will save all the information related to this event.

Another function of the confirmer is to provide the sequence of the units sort by the time when the unit experiences the event and the time difference of each two continuous units. This information will be the input information for the localization program to estimate the disturbance location.

## 5.3 Disturbance Event Localization Algorithm

When algorithm detects that there is some disturbance happen in the system to force the frequency in different locations drop in a sequence, the algorithm will record the frequency drop time at each location. From the observation of several cases, it is very clear that the times of the frequency experience disturbance at different locations are different, and the time delay of each two locations can be calculated from the time stamp attached with the data package.

In steady state, the power system frequency is the same in different parts of an interconnected system. This is not the case during an initial period following the trip of a big generator or a load and before a new equilibrium in active power has been achieved. This type of disturbance creates an imbalance of active power in the system and changes the frequency in different parts of the system. During a transient period, the system frequency $f$ and the rate of change of system frequency $df/dt$ are not the same throughout the system. In locations close to the disturbance, the absolute value of the frequency derivative $|df/dt|$ is much higher than in regions far away from disturbance. This phenomenon can be used in the feature extraction and disturbance classification method to distinguish between remote and close-by generation trips.

The slope of the local system frequency variation on its first "swing" can be used to assess how close a disturbance is located to the FDR. Using multiple FDR at different sites in the system may provide accurate information to estimate the actual location of the disturbance in some case. The time difference is because that the distances of fault event location to the FDR locations are different.

The algorithm of fault event location is based on the time delay of each FDR experience the fault event. With this information, the fault event location can be triangulated through some classical method of fault determination in similar areas. Here, the algorithm of Time Difference of Arrival (TDOA), which is widely used in seismology, sonography, electronic intelligence, and geophysical remote sensing and so on, is introduced to solve the disturbance location issue.

### 5.3.1 Geographical Modeling of Localization Issue

The assumption of TDOA is that the wave, which can be electromagnetic wave, seismic wave and so on, will propagate in all direction with the same speed. Based on this assumption, if some stations or sensors geographically dispersed in the detection system, the time when the wave arrives at each sensor is different. With the time delay between each two sensors and the location information of each sensor, the original source of this wave can be located with some algorithm to get the solution of the nonlinear optimal equation set.

This is the basic idea of triangulation of the location of the disturbance, just use the geographical location and distance to build a pure geographical model.
Put all the units in a map and get the coordination of each unit:
Unit_1 ($a_1, b_1$), Unit_2 ($a_2, b_2$), ……, Unit_n ($a_n, b_n$)
Together with the Time difference of arrival information:

$$\begin{cases} \Delta t_1 = t_2 - t_1 \\ \Delta t_2 = t_3 - t_2 \\ \cdots \\ \Delta t_{n-1} = t_n - t_{n-1} \end{cases}$$

Here we define $d_1, d_2, \cdots d_n$ as the distances from the unknown disturbance location to each unit, and define the disturbance location as (x, y), the speed of frequency propagation as c

$$\begin{cases} d_1 = \sqrt{(x-a_1)^2 + (y-b_1)^2} \\ d_2 = \sqrt{(x-a_2)^2 + (y-b_2)^2} \\ \cdots \\ d_n = \sqrt{(x-a_n)^2 + (y-b_n)^2} \end{cases}$$

Based on the simple model, the difference of distances should be the product of speed and time difference, so we can get the following equations:

$$\begin{cases} d_2 - d_1 = \Delta t_1 \times c \\ d_3 - d_2 = \Delta t_2 \times c \\ \cdots \\ d_n - d_{n-1} = \Delta t_{n-1} \times c \end{cases}$$

In this equation set, the known quantities are the coordinates of each unit and the time difference from FNET system; the unknown quantities are the coordinates of the disturbance location and the speed c. Because the number of equation in this set is always more than three, the basic idea is to get the optimal solution of this nonlinear equation set to get the unknowns.

Here we define the equation set as:

$$\begin{cases} f_1 = d_2 - d_1 - \Delta t_1 \times c \\ f_2 = d_3 - d_2 - \Delta t_2 \times c \\ \cdots \\ f_{n-1} = d_n - d_{n-1} - \Delta t_{n-1} \times c \end{cases}$$

The solution of this equation set should make all these functions be zero, while the optimal solution should make these functions infinitely approach zero. There are many algorithms to solve this nonlinear optimal issue, such as least square solution and so on.

### 5.3.2 TDOA Algorithm Design

In this algorithm, the assumption is the speed of frequency propagation in each direction is the same, so the time delay of each FDR experienced the frequency drop can be used to determine the location of event. If the speed of frequency propagation is different in different direction, this difference can be added as a weight factor in the final solution.

The time of n FDR experienced event are $t_1, t_2, \cdots t_n$ the location $(x_0, y_0)$ and event starting time $t_0$ are the parameter, which need to be computed to get the minimum of the target equation (1):

$$\phi(t_0, x_0, y_0) = \sum_{i=1}^{n} r_i^2 \tag{1}$$

where $r_i$ is the time different

$$r_i = t_i - t_0 - T_i(x_0, y_0) \tag{2}$$

$T_i$ is the computed time from event location to FDR.

So the problem becomes is a multidimensional unconstrained nonlinear minimization question.

To make the target equation minimum is to solve this differential equation

$$\nabla_{\boldsymbol{\theta}} \phi(\theta) = 0 \tag{3}$$

Where $\theta = (t_0, x_0, y_0)^T$, $\nabla_{\boldsymbol{\theta}} = (\frac{\partial}{\partial t_0}, \frac{\partial}{\partial x_0}, \frac{\partial}{\partial y_0})^T$.

For convenience, defining

$$g(\theta) = \nabla_{\boldsymbol{\theta}} \phi(\theta) \tag{4}$$

So from equation (3), use a random tentative solution $\theta^*$ near the real solution $\theta$ and the differential vector $\delta\theta$ to satisfied

$$g(\theta^*) + [\nabla_{\boldsymbol{\theta}} g(\theta^*)^T]^T \delta\theta = 0 \tag{5}$$

That is

$$[\nabla_{\boldsymbol{\theta}} g(\theta^*)^T]^T \delta\theta = -g(\theta^*) \tag{6}$$

From the definition of $\phi$, the equation of (6) can be:

$$\sum_{i=1}^{n}\left[\frac{\partial r_i}{\partial \theta_j}\frac{\partial r_i}{\partial \theta_k} + r_i \frac{\partial^2 r_i}{\partial \theta_j \partial \theta_k}\right]_{\boldsymbol{\theta}^*} \delta\theta_j = -\sum_{i=1}^{n}\left(r_i \frac{\partial r_i}{\partial \theta_k}\right)_{\boldsymbol{\theta}^*} \tag{7}$$

If $\theta^*$ is not far from the real solution $\theta$, the $r_i(\theta^*)$ and $\left(\frac{\partial^2 T_i}{\partial \theta_j \partial \theta_k}\right)_{\boldsymbol{\theta}^*}$ will be small enough, and if the second order derivative can be ignored, the equation (7) can be simplified:

$$\sum_{i=1}^{n}\left[\frac{\partial r_i}{\partial \theta_j}\frac{\partial r_i}{\partial \theta_k}\right] = -\sum_{i=1}^{n}\left(r_i \frac{\partial r_i}{\partial \theta_k}\right)_{\theta^*} \tag{8}$$

In addition, in format of matrix:

$$A^{\mathrm{T}} A \delta\theta = A^{\mathrm{T}} r \tag{9}$$

Where $A = \begin{pmatrix} 1 & \frac{\partial T_1}{\partial x_0} & \frac{\partial T_1}{\partial y_0} \\ \vdots & \vdots & \vdots \\ 1 & \frac{\partial T_n}{\partial x_0} & \frac{\partial T_n}{\partial y_0} \end{pmatrix}_{\theta^*}$ , $r = \begin{pmatrix} r_1 \\ \vdots \\ r_n \end{pmatrix}$.

While if the second order derivative can not be ignored, the equation (7) can be in nonlinear format of matrix:

$$\left[\mathbf{A}^{\mathrm{T}}\mathbf{A} - \left(\nabla_{\boldsymbol{\theta}} \mathbf{A}^{\mathrm{T}}\right)\mathbf{r}\right]\delta\boldsymbol{\theta} = \mathbf{A}^{\mathrm{T}}\mathbf{r}\,. \tag{10}$$

From the equation (9), (10) to get $\delta\boldsymbol{\theta}$, use $\boldsymbol{\theta} = \boldsymbol{\theta}^* + \delta\boldsymbol{\theta}$ as a new attempt point and solve the equation again, until the $\phi$ or $\phi_r$ is small enough, then get the estimated solution $\widehat{\boldsymbol{\theta}}$.

If n is the length of x, a simplex in n-dimensional space is characterized by the n+1 distinct vectors that are its vertices. In two-space, a simplex is a triangle; in three-space, it is a pyramid. At each step of the search, a new point in or near the current simplex is generated. The function value at the new point is compared with the function's values at the vertices of the simplex and, usually, the new point, giving a new simplex, replaces one of the vertices. This step is repeated until the diameter of the simplex is less than the specified tolerance.

### 5.3.3 Location Sample Cases Analysis

In this section, there are two sample cases analyzed by the Matlab location program, please refer to the Appendix for the detail of the program. The first one is the nuclear power plant trip event, which located at Davis Besse and happened on Aug. 4, 2004. The second sample case is the generation tripped at Watts Bar on Sep. 19, 2004. In the figures of the following two cases, asterisk stands for FDR units used in estimation; diamond stands for the estimated location with TDOA method and square stands for confirmed disturbance real location.

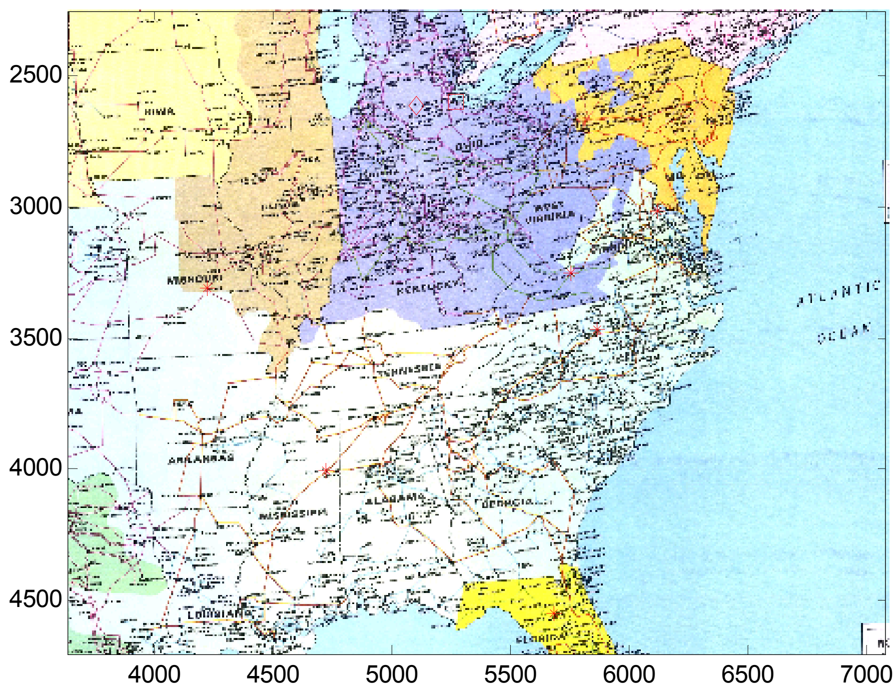



Figure 5.11 Location Sample Case at Davis Besse

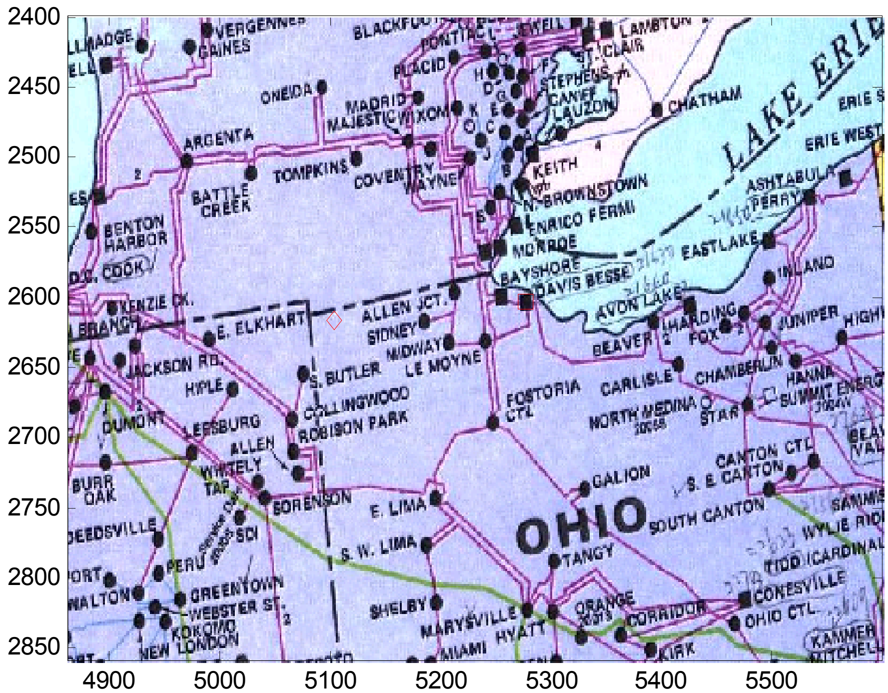



Figure 5.12 Detailed Illustration of Estimated Location and Real Location

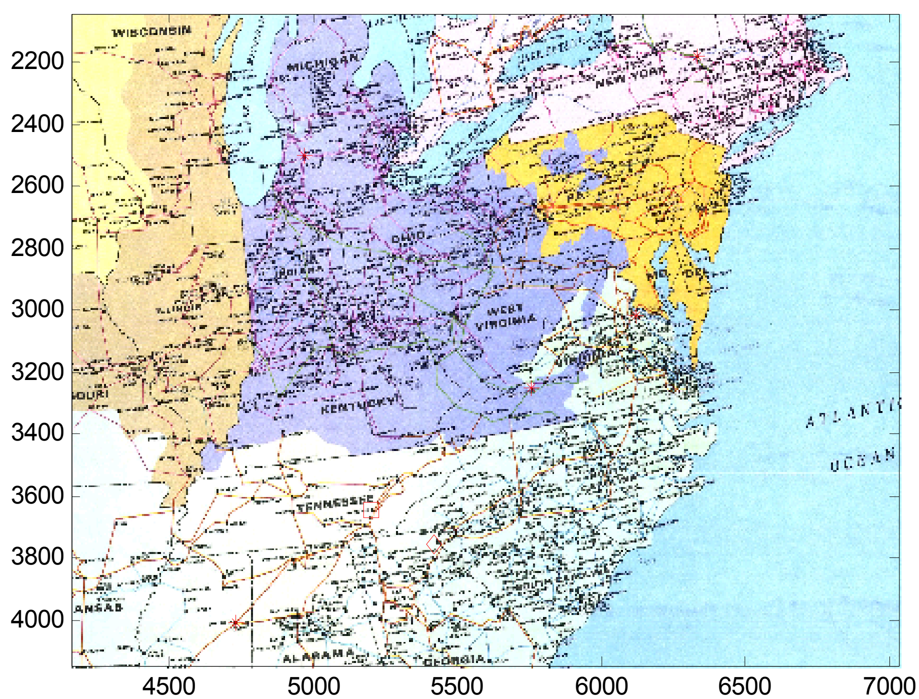



Figure 5.13 Location Sample Case at Davis Besse

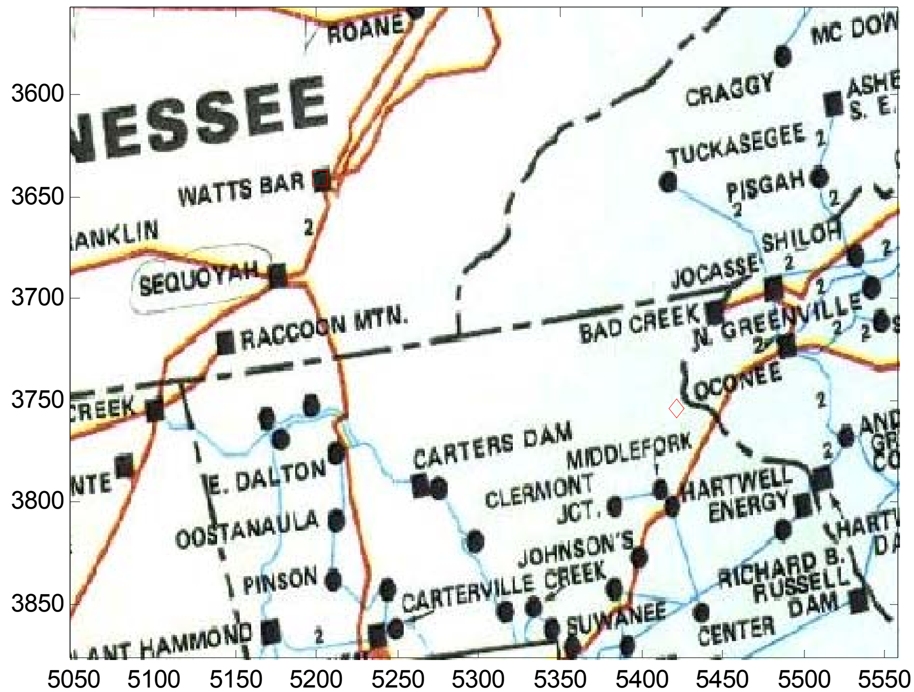



Figure 5.14 Detailed Illustration of Estimated Location and Real Location

The error distance in the first case is 75 miles and in the second case is 105 miles. The error of location is affected by the difference of frequency wave speed in different directions and the topology of the transmission lines. Until now, the wave propagation speed is still under research, and from the simulation result, the speed in different direction is different, so there must have some error in the location estimation. If the speed of wave propagation can be introduced into the equations as a weight factor to each single equation, the accuracy of this algorithm can be significantly improved.

### 5.3.4 Network Model of Power Grid and the Definition of Electrical Distance

Actually, use the TDOA method, with the least square algorithm or other algorithm to get the optimal solution of the generator location, there is still some error in spite of the error of the algorithm itself. Then use look-up table model to figure out the most possible generator will be the disturbance source. Therefore, with the estimation of the location from the TDOA method, a rough location of the disturbance can be derived for the further accurate location to the exact power plant with the generator, which leads to the disturbance to the system.

With the analysis on some known cases, the exact power plant locates in a geographical circle with the coordination of the estimated location as center and a certain distance (100 miles) as the radius. Because the power plants are no so dense geographically, so there will only be several power plants in this estimated circle area. These power plants can create a possible table. Therefore, the issue comes to how to determine which power plant should be the disturbance one. Another information can be used for determination is the changed generation in the disturbance. With the detailed description of the next section, the generation can be estimated with empirical equation. Together with this information, those power plants with the lower capacity than the changed generation should be taken out of the table, and only those power plants with larger capacity will stay in the table. Sometimes, only one power plant will stay in the table, that one can be the answer; while sometimes, there are still more than one power plant can be the possible one. At this time, the possibility of each power plant will be evaluated to give a list sort by the possibility.

This network model is very rough and lack of theoretic support. A possible idea is to define an electrical distance between the power plant and substation to replace the pure geographical distance. If such model can be built, the solution of TDOA will be greatly improved. While the definition of electrical distance involves in the different voltage level transformer, the propagation routine of electrical parameters, many power system component modeling and some other issues. The current model is based on the electromagnetic characteristics of power system, while the frequency response related to the electromechanical characteristics of the power system. From the academic view, how to define this model is still under research.

## 5.4 Generation Estimation in Generator Tripping Event

In the power system, if there is a relative significant generation tripped in the system, the frequency will experience a sudden drop due to the power mismatch between generation and load.

The estimation of tripped generation in fault event analysis is based on the relation of the frequency and active power balance in the system. It is known that in power system the real-time frequency and the rate of frequency change *df/dt* of the whole system are the most important parameters in calculation or estimation of the imbalance between load and generation.

In large interconnected power systems, such as WECC and EUS, serious frequency falls now require a very heavy loss of generation. In WECC, there are many sudden frequency drop occurred because the capacity of WECC system is not as huge as EUS. Hence, when a certain amount of generation tripped in WECC and EUS, the frequency response is more sensitive in WECC than in EUS. This is due to the relationship of frequency change and inertia of the electric power system.

$$\Delta P_d = P_{msystem} - P_{esystem} = 2\frac{d\omega}{dt}H_{system},$$

There are many frequency estimation or predict algorithm to get these two parameters. Now, with the help of wide-area measurement devices (PMU and FDR), the frequency and the rate of frequency change can be easily measured and provided for this application. This means the rate can be calculated using the initial samples after the disturbance of the generators' electrical angular velocities at intervals of a constant time interval, and the $H_{system}$ is the sum of all generators' inertia constants. So the amount of imbalance active power $\Delta p$ can be calculated in the central server of FNET with frequency information.

From this analysis, if the system inertia is known and rate of frequency change can be calculated from FNET frequency information, the amount of imbalanced active power $\Delta p$ can be calculated. In WECC and EUS system, the system inertia can be calculated through the empirical equations build by the cases, which have already occurred, and the information of these cases is known.

### 5.4.1 Definition of Starting and Ending Time in a Frequency Drop Event

In order to calculate the generation, the frequency shift during the disturbance is needed as the input information, and so it is important to define the starting and ending time of disturbance.

In the program, the trigger method is used to detect the abnormal frequency deviation. When the deviation reaches the setting threshold, which depends on the period length in the calculation of frequency deviation, this means an event is detected at time T_event, then go back the deviation array to search the point, which is larger than zero and closest to T_event, the time of this point is defined as T_start. After event happens, search the frequency deviation until it go back to be positive, the time of the point firstly becomes positive is T_end. So period of disturbance should be from T_start to T_end. Normally, the period lasts for 2~8 seconds in the known cases, while this length can vary according to the different interconnection and different scenarios.

### 5.4.2 Definition of the Frequency Shift during Disturbance

With the definition of disturbance start and end time, the pre-event average frequency should be the mean of the frequency points in the 5 seconds before T_start, [T_start-5, T_start], and the post-event average frequency should be mean of the frequency points in the 5 seconds after T_end, [T_end, T_end+5].
With this definition, we can get

$$f_{pre} = AVERAGE(f_{St-50} : f_{st})$$

$$f_{post} = AVERAGE(f_{end} : f_{end+50})$$

therefore, the frequency shift during the disturbance is the difference between these two averages.

### 5.4.3 Training Algorithm for the Coefficient of Empirical Equation

In order to get the coefficient β of the empirical equation, some known cases are used to train this factor with the training method.

In WECC system, there are four cases reported with the amount of tripped generation and event date and time (TableTABLE 5.1). The frequency change during the event period can be found and calculated from the frequency database.

Table 5.1 Generation Tripped Events in WECC

| Date | Tripped Generation | Frequency change |
|---|---|---|
| 06/29/2004 | 600MW | 0.075Hz |
| 06/30/2004 | 500MW | 0.065Hz |
| 07/02/2004 | 500MW | 0.068Hz |
| 07/04/2004 | 800MW | 0.095Hz |

From these four cases, the coefficient *dP/df* of the empirical equation between the tripped generation and frequency drop amount within a fixed time can be derived:

$$\frac{dP}{df}_1 = 600/0.075 = 8000 MW/Hz$$

$$\frac{dP}{df}_2 = 500/0.065 = 7692.3 MW/Hz$$

$$\frac{dP}{df}_3 = 500/0.068 = 7352.9 MW/Hz$$

$$\frac{dP}{df}_4 = 800/0.095 = 8421.1 MW/Hz$$

$$\frac{dP}{df}_{Aver} = \frac{\sum_{i=1}^{4}\left(\frac{dP}{df}_i \times dP_i\right)}{\sum_{i=1}^{4} dP_i} = \frac{(8000\times 600 + 7692.3\times 500 + 7352.9\times 500 + 8421.1\times 800)}{(600+500+500+800)}$$

So, $\frac{dP}{df}_{WECC} = 7866 MW/Hz$

This coefficient is used in WECC system, while for the EUS system, the capacity is about 4 times the capacity of WECC, so the coefficient of EUS supposes to be about 4 times coefficient of WECC, so we get: $\frac{dP}{df}_{EUS} = \frac{dP}{df}_{WECC} \times 4 = 7866 \times 4 = 31464 MW/Hz$

### 5.4.4 Validation of Coefficient with Event in WECC

There was a significant event in WECC occurred on Jun. 14, 2004, and the FNET system recorded the frequency information of this event (Figure 5.15). From the trend of the frequency decline, there were at least two sets of generators tripped. The first tripping happened at 14:40:34, and the second tripping happened 21 seconds later (14:40:55). The power loss on the second tripping was much larger than the first one, and the slope of the initial swing of the second tripping was greater than the first. The frequency declined to about 59.57Hz, and then gradually recovered to the normal operating state at 14:58:17. The gradual recovery may be due to the combinations of governor reactions and automatic generation control (AGC), which is the secondary frequency control in power plants.

When this event occurred, there is only one FDR in WECC system, so the event location cannot be derived from the FNET. The event location triangulation needs at least three FDR units in the power grid.

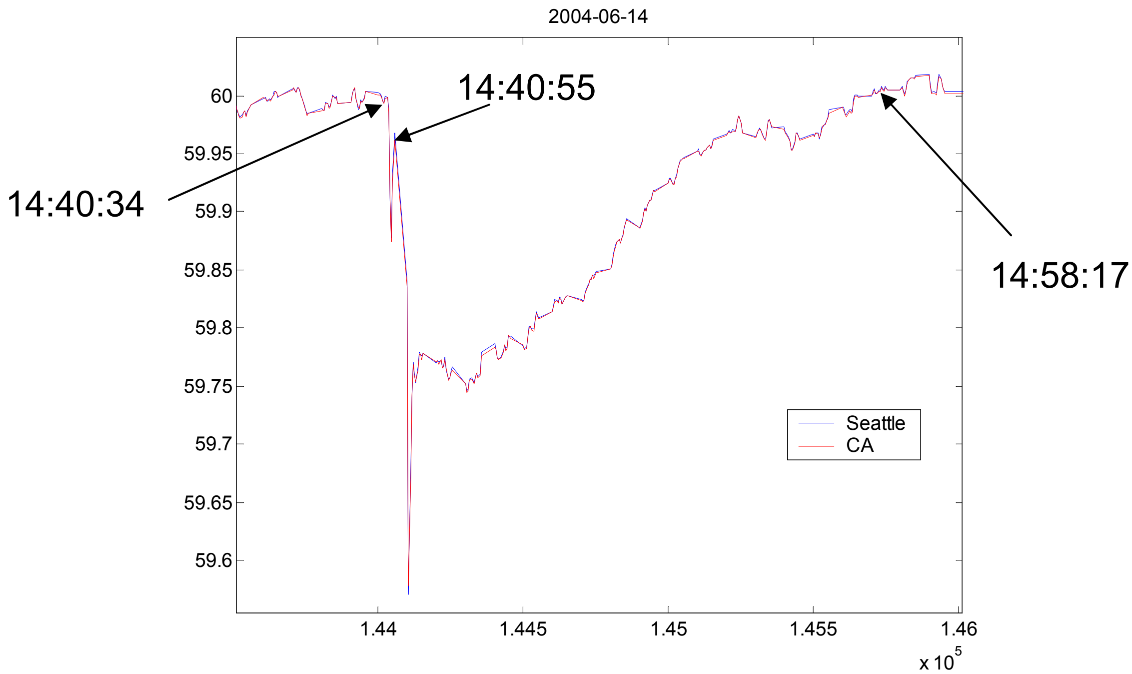



Figure 5.15 Frequency of FDR at CA and Seattle in the Jun.14, 2004 generator trip event in WECC

In the first tripping, the lost generation should be: $7866 \times 0.13 = 1022.58MW$, and the lost generation in the second tripping should be: $7866 \times 0.45 = 3539.7MW$. So the total lost generation in this event should be 4562.58MW. It is reported that the lost generation in this event is about 4800MW.

For the first frequency drop, the amount of frequency change is:

$$\Delta f_1 = 59.998 - 59.8745 = 0.1235Hz,$$

and the second drop, $\Delta f_2 = 59.9617 - 59.52 = 0.4417Hz$. So the generation tripped in the first drop:

$$\Delta P_1 = \Delta f_1 \times \frac{dP}{df}_{WECC} = 0.1235 \times 7866 = 971.45MW,$$

and in the second drop: $\Delta P_2 = \Delta f_2 \times \frac{dP}{df}_{WECC} = 0.4417 \times 7866 = 3474.4MW$,

so the total tripped generation in this event is:

$$\Delta P = \Delta P_1 + \Delta P_2 = 971.45 + 3474.4 = 4445.9MW$$

It is reported that there are three generators tripped and there is 4800MW generation lost, so the error of tripped generation estimation is:

$$\delta = (\Delta P_{real} - \Delta P) / \Delta P_{real} = \frac{4800 - 4445.9}{4800} \times 100\% = 7.37\%$$

## 5.5 Generator Tripped Fault Events Analysis

There are more FDR units in the EUS system than that in WECC system, while the capacity of the EUS System is much larger than WECC system. In this means, when the same amount of generation is tripped in the two systems, the response of WECC is more distinct than that in the EUS system. The FNET system is sensitive enough to catch the small frequency drop. With frequency information from FDR units in the EUS system, if an unexpected event occurs, the location of this event can be estimated by triangulation analysis and the amount of generation change can be estimated. The FNET system started running from this summer, during this period there are four significant generator tripped events in EUS as we know. These four events are listed in the following TableTABLE 5.2 with date and detailed time.

Table 5.2 Four Generator Tripped Events to be Analyzed in EUS

| Date | Time(GMT) |
|---|---|
| Aug.4, 2004 | 14:23:08 |
| Aug.6, 2004 | 12:36:47 |
| Sep.19,2004 | 8:55:57 |
| Nov.23, 2004 | 15:59:53 |

### 5.5.1 Fault Event of Generator Tripped on Aug.4, 2004

The first case happened on Aug. 4, 2004, when a generator tripped and the frequency of the EUS system declined but the decline start time and the slope of the decline were different at different locations in the EUS system. The FNET system recorded this event. Figure 5.16 is raw frequency data during the event period, and the time range is 3 minutes including pre-event and post-event period. Figure 5.17 is the detailed frequency data, and the time range is 20 seconds.

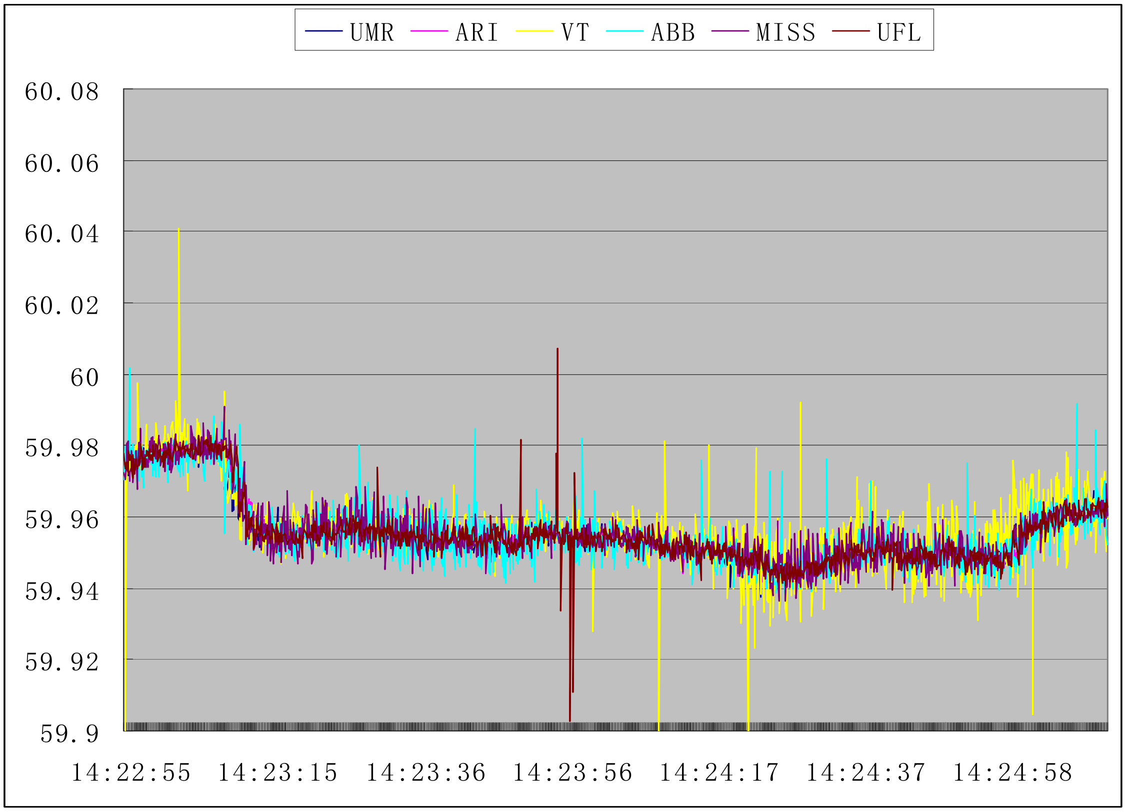



Figure 5.16 Raw frequency data of Aug. 4, 2004 event during the event period (3minutes)

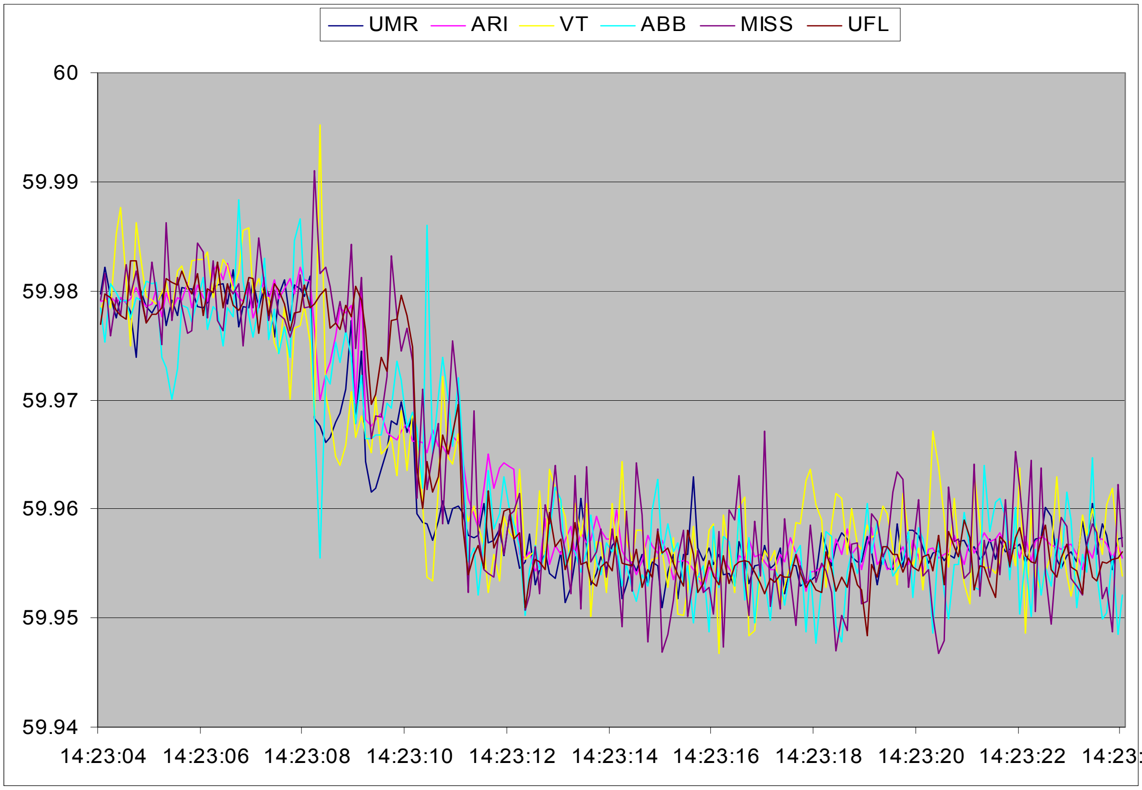



Figure 5.17 Detailed raw frequency data of Aug. 4, 2004 event (20seconds)

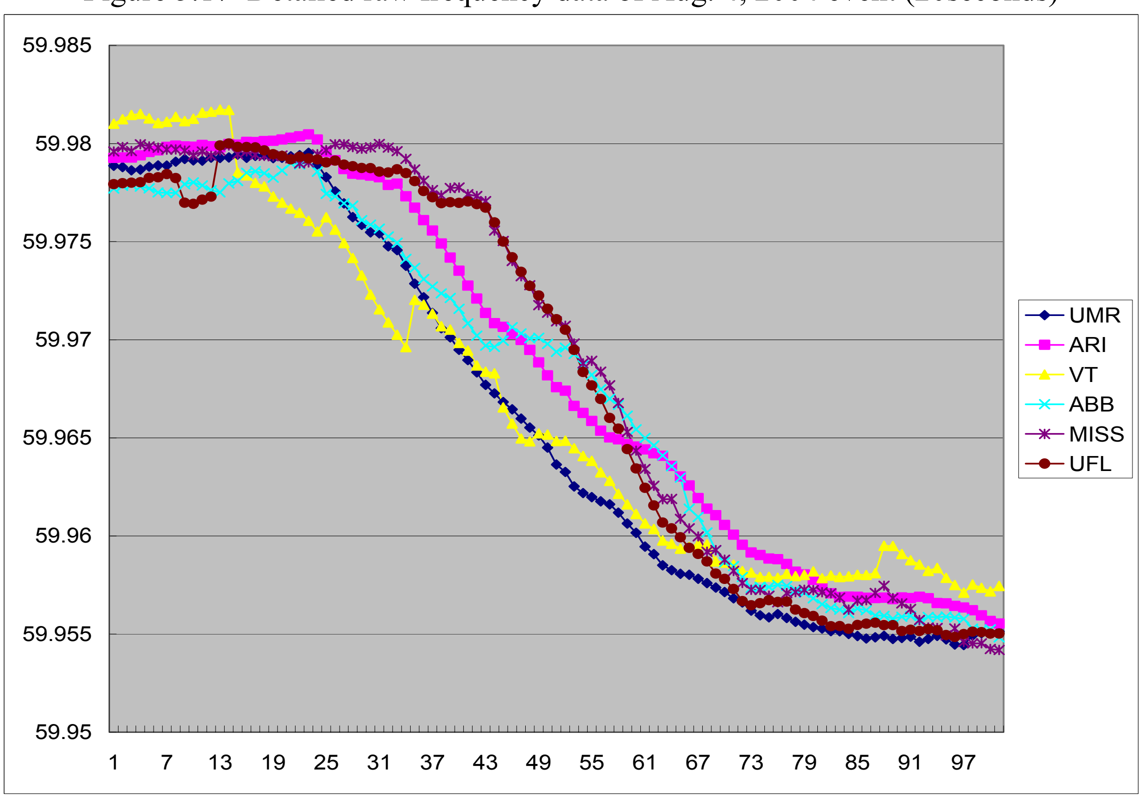



Figure 5.18 10-point average frequency of Aug. 4, 2004 event (10seconds)

The following figure is the 10-point average frequency data of each FDR. From the figures, it's very clear that before the event happened, the EUS system frequency was around 59.98Hz, and the units in ARI, VT, UMR, and ABB firstly experienced frequency drop at 14:23:08.8; then units in MISS and UFL experienced frequency drop after 1 second; at last the frequency went down to 59.955Hz at 14:23:12.8.

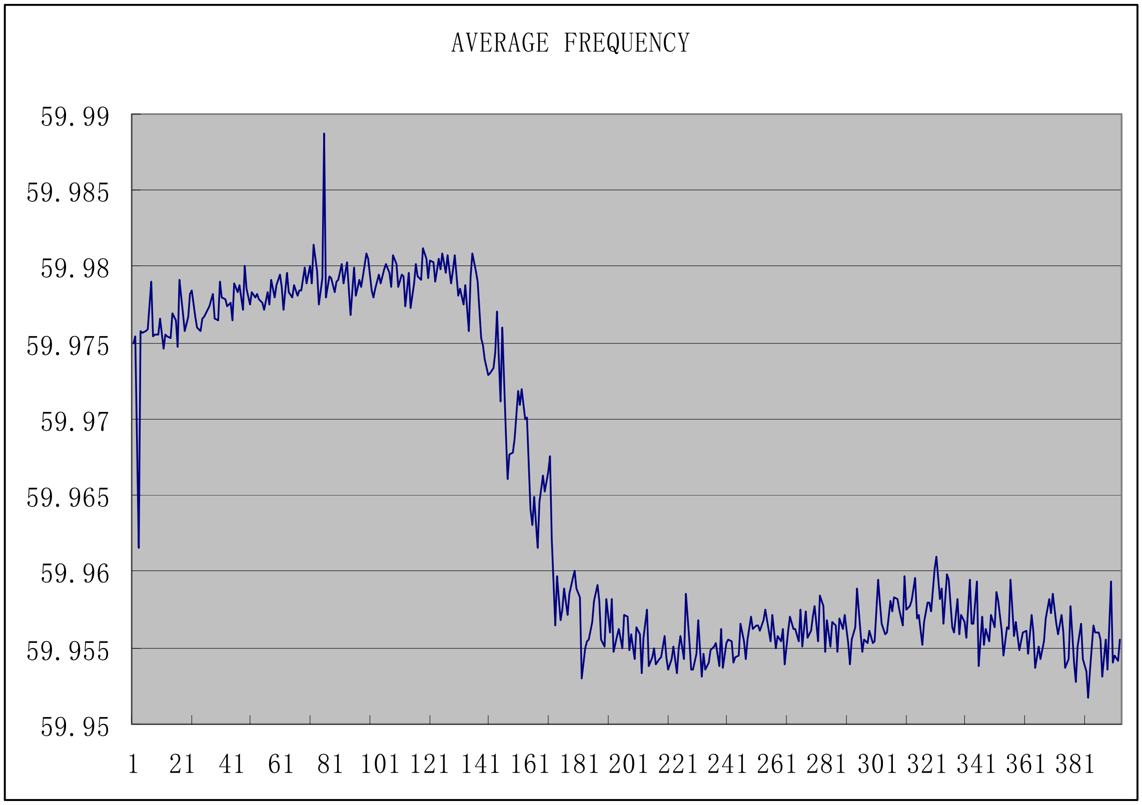



Figure 5.19 Average of raw frequency data from 6 FDR Units of Aug. 4, 2004 event

Figure 5.19 is the average of frequency data of all six FDR units that recorded this event. The amount of frequency change in this event can be calculated from this figure. In this case, frequency change is 0.025Hz, so estimated amount of tripped generation can be calculated from the empirical equation:

$$\Delta P = \Delta f \times \frac{dP}{df}_{EUS} = 0.025 \times 31464 \approx 786.6MW$$

while the actual tripped generation was around 870MW, so the error of tripped generation estimation is:

$$\delta = (\Delta P_{real} - \Delta P) / \Delta P_{real} = \frac{870 - 786.6}{870} \times 100\% = 9.58\%$$

From the delay time difference and the amount of frequency decline within a fixed time, the event location can be estimated as shown in Figure 5.20. Estimated triangulation shows the event should locate in the joint area of Michigan, Indiana and Ohio. The blue dot is the estimated event location, while the real event was located at the square on the right side. The error of location is affected by the difference of frequency wave speed in different directions and the topology of the transmission lines.

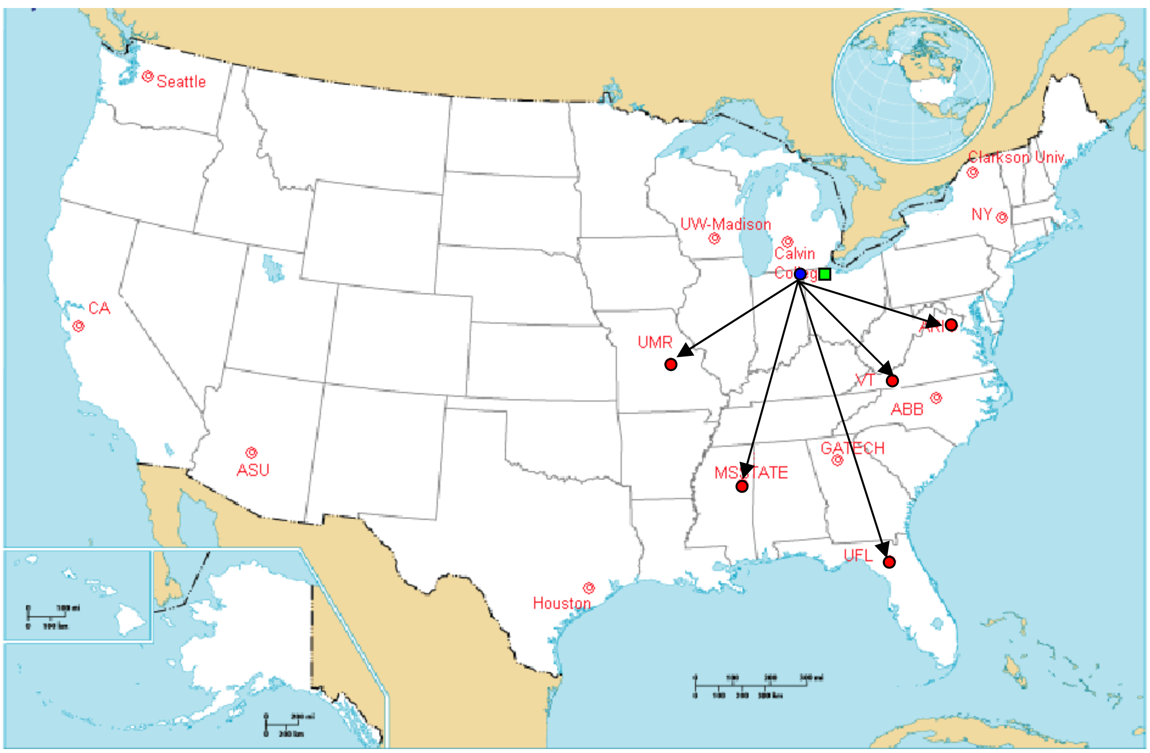


Figure 5.20 Triangulation of tripped generator location of Aug. 4, 2004 event (eyeball)

## 5.5.2 Fault Event of Generator Tripped on Aug.6, 2004

The second case happened on Aug. 6, 2004. Figure 5.21 is raw frequency data during the event period, and the time range is 15 minutes including pre-event and post-event period. Figure 5.22 is the detailed frequency data, and the time range is 20 seconds. Figure 5.23 is the 10-point average frequency data of each FDR. From the figures, it is very clear that before the event happened, the EUS system frequency was around 60Hz. The FDR units at VT and MISS almost experienced the event at the same time, 0.9 second later, UFL and ABB experienced frequency drop; at last the frequency went down to 59.9596Hz.

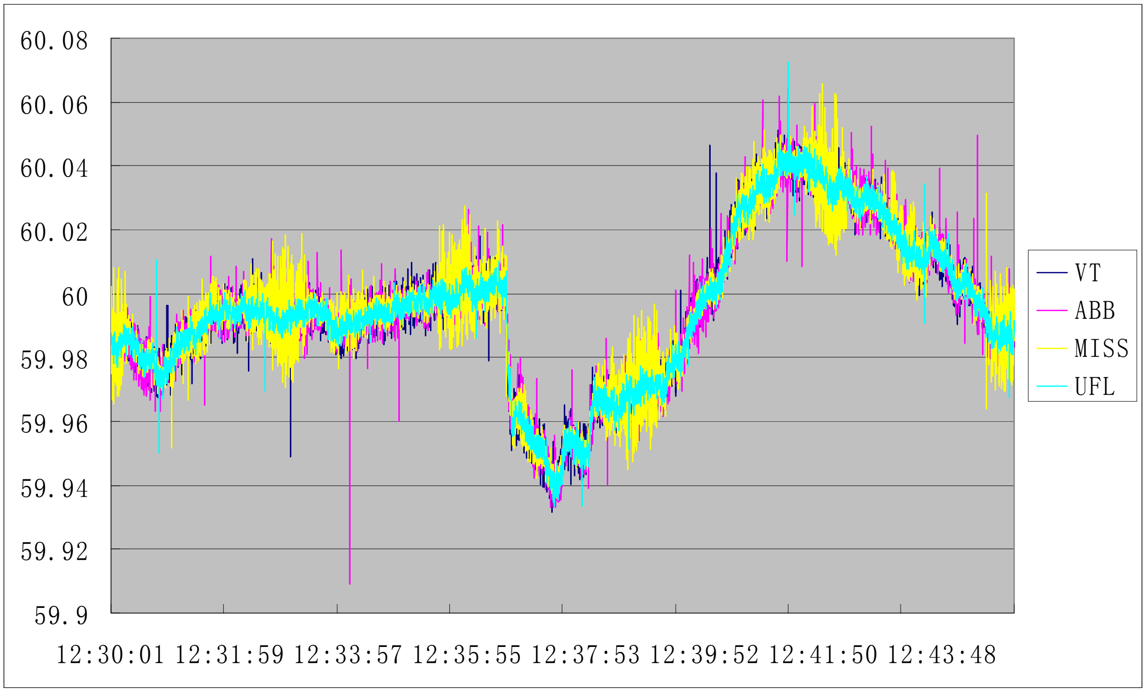



Figure 5.21 Raw frequency data of Aug. 6, 2004 event (15minutes)

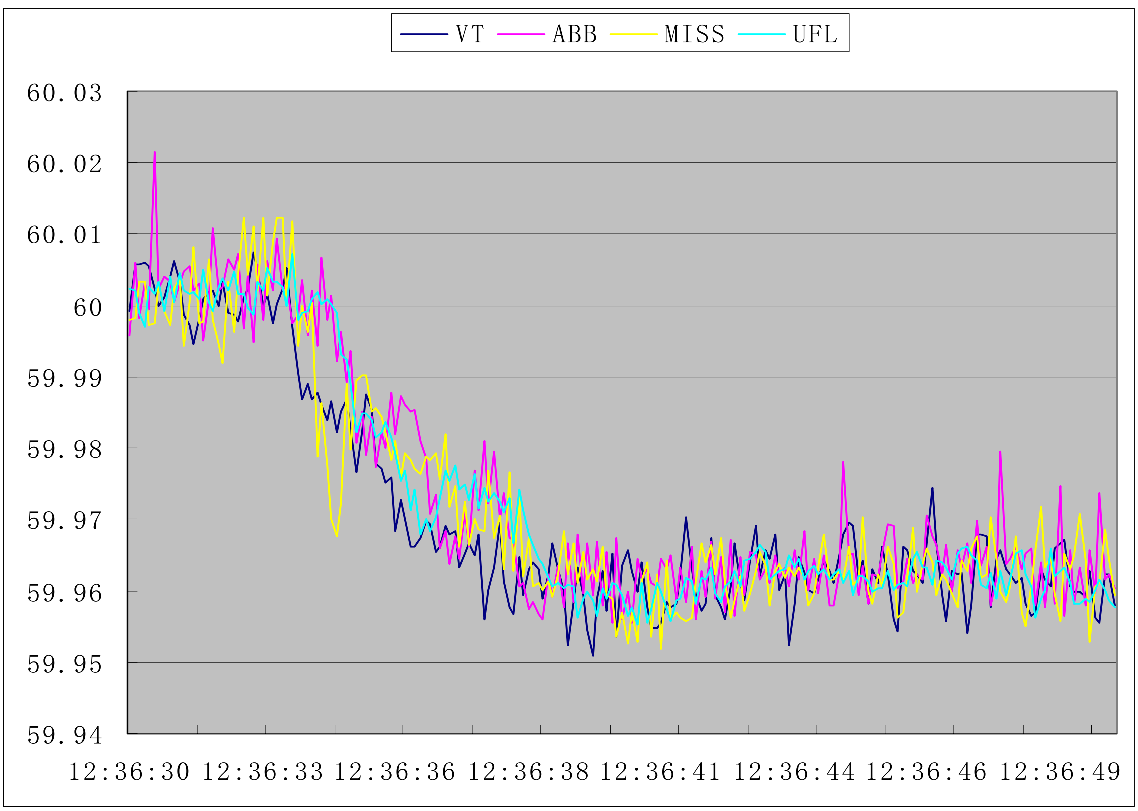



Figure 5.22 Detailed raw frequency data of Aug. 6, 2004 event (20seconds)

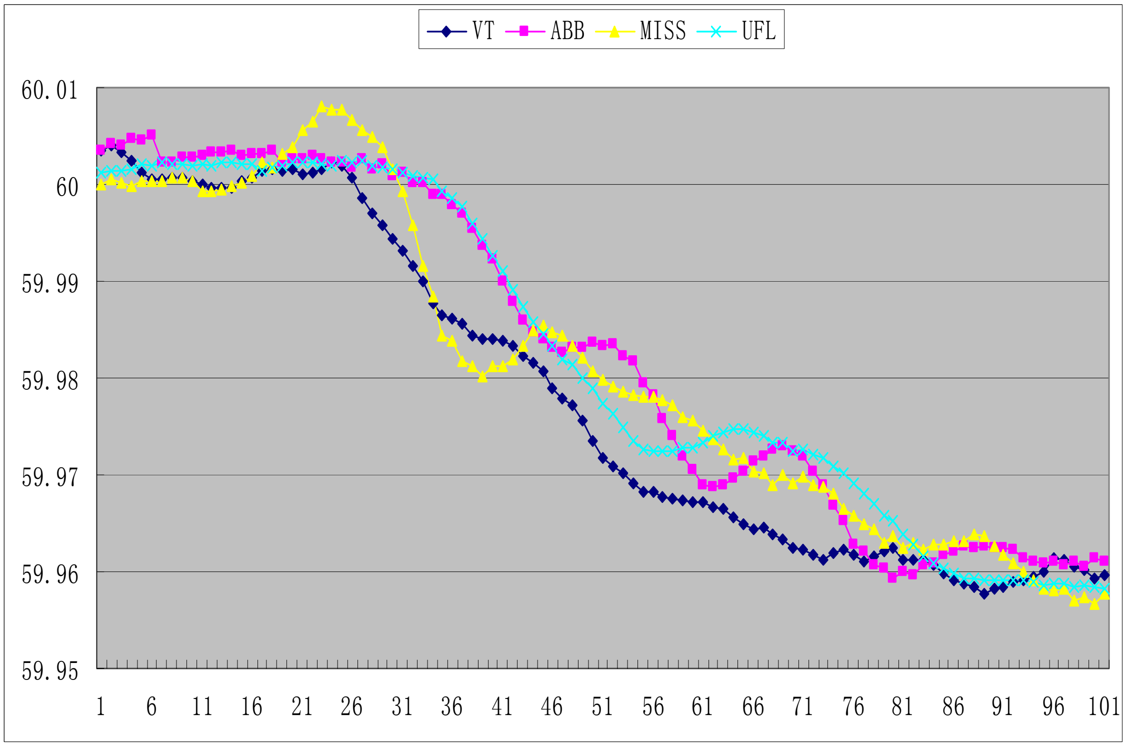



Figure 5.23 10-point average frequency of Aug. 6, 2004 event (10seconds)

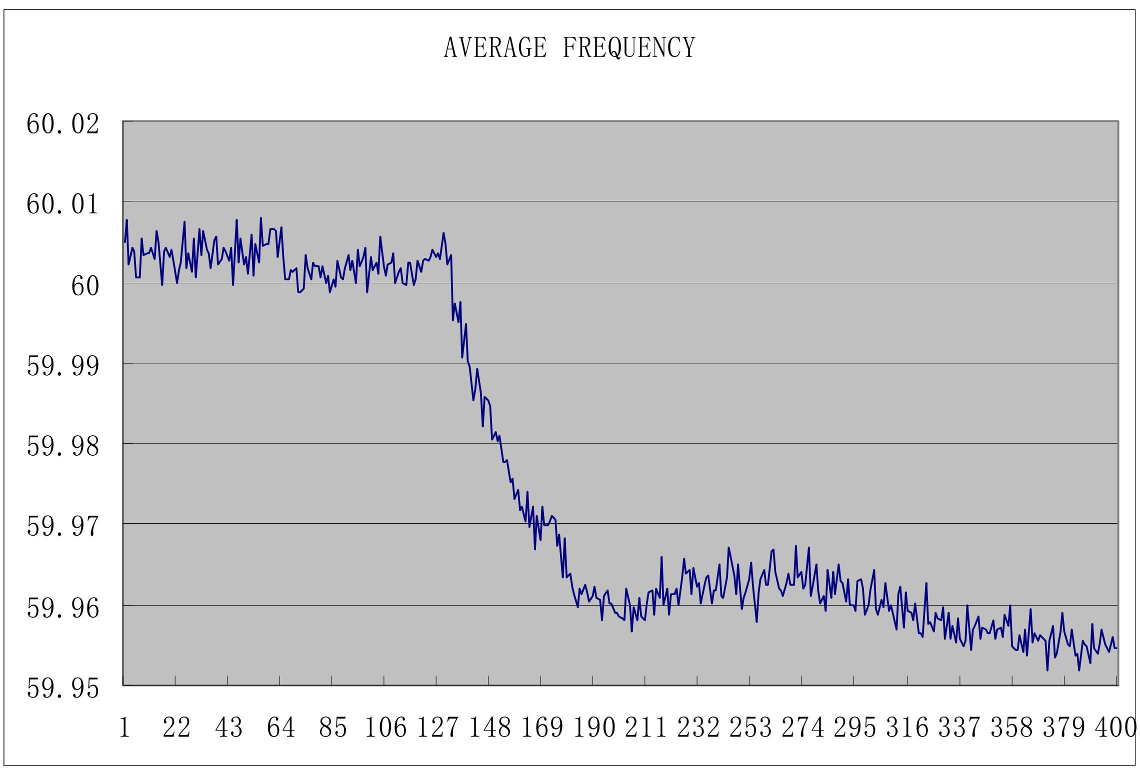



Figure 5.24 Average of frequency from 4 FDR units of Aug. 6, 2004 event

The previous figure is the average of frequency data of four FDR units that recorded this event. The amount of frequency change in this event can be calculated from this figure. In this case, average frequency change is 0.0436Hz, so estimated amount of tripped generation can be calculated from the empirical equation:

$$\Delta P = \Delta f \times \frac{dP}{df}_{EUS} = 0.0436 \times 31464 \approx 1371.9MW$$

while the actual tripped generation was around 1300MW, so the error of tripped generation estimation is:

$$\delta = (\Delta P_{real} - \Delta P) / \Delta P_{real} = \frac{1300 - 1371.9}{1300} \times 100\% = -5.53\%$$

From the average frequency data, frequency drop sequence: VT and MISS almost the same to experience the event, 0.9 second later, UFL and ABB experience it. From the raw frequency curve, the frequency of VT dropped firstly, while the frequency of MISS is most affected by the disturbance compared with the other three frequencies. From the delay time difference, the event location can be estimated as shown in following figure. Estimated triangulation shows the event should locate in the middle north area of Tennessee. The blue dot is the estimated event location, while the real event was located at the square on the left lower side.


Figure 5.25 Triangulation of tripped generator location of Aug. 6, 2004 event

## 5.5.3 Fault Event of Generator Tripped on Sep.19, 2004

The third case occurred on Sep. 19, 2004. The EUS System experienced a sudden frequency decline (Figure 5.26), and the FNET system recorded the frequency information at each of the FDR units. Figure 5.26 is raw frequency data during the event period, and the time range is 3 minutes including pre-event and post-event period. Figure 5.27 is the detailed frequency data, and the time range is 20 seconds. Figure 5.28 is the 10-point average frequency data of each FDR.

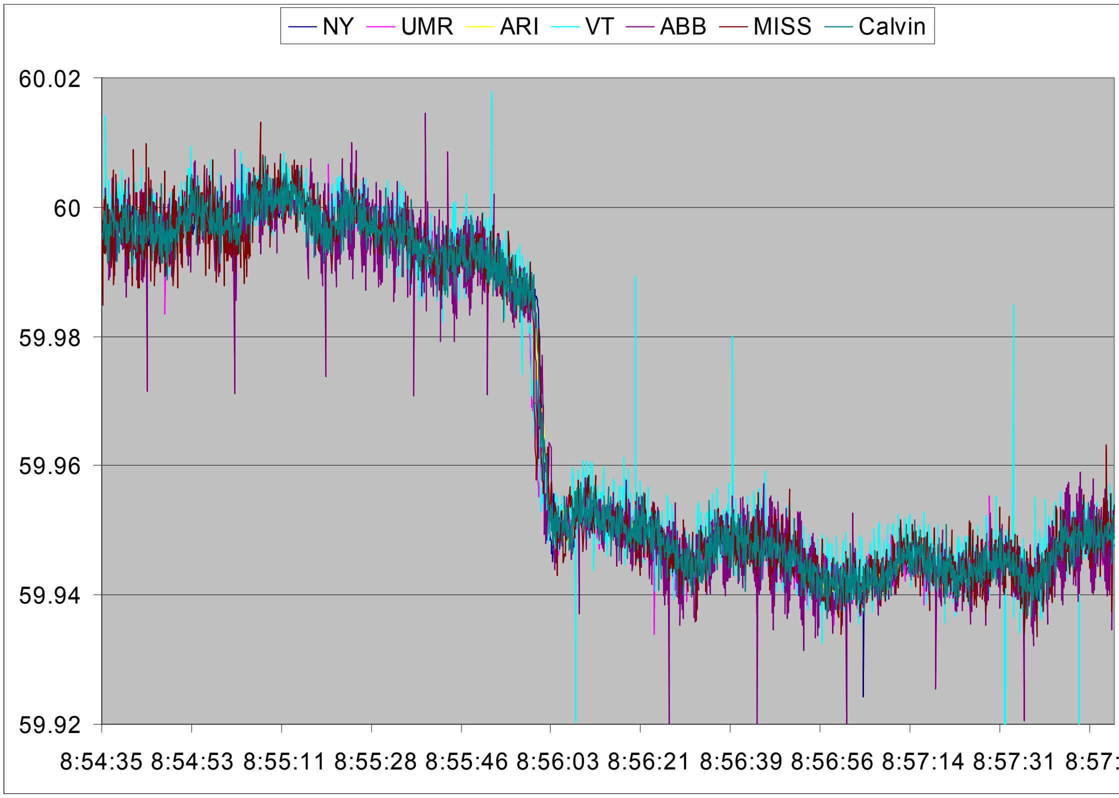



Figure 5.26 Raw frequency data of Sep. 19, 2004 event (3minutes)

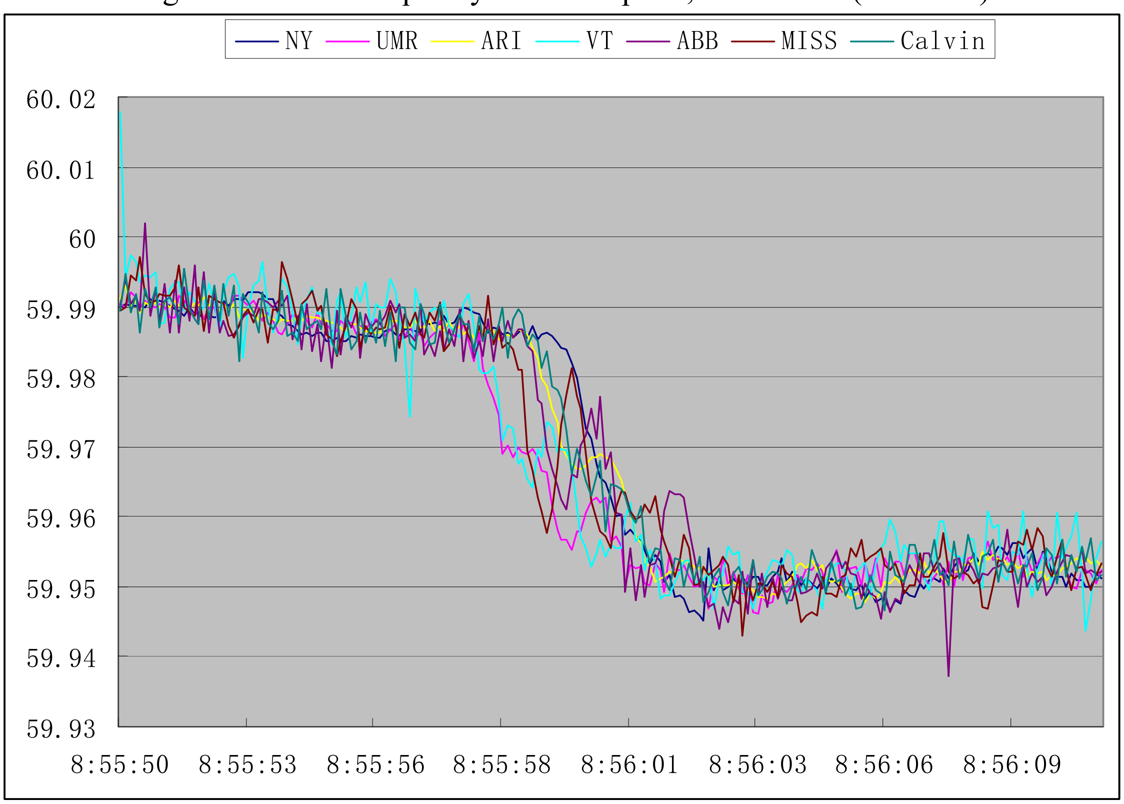



Figure 5.27 Detailed raw frequency data of Sep. 19, 2004 event (20seconds)

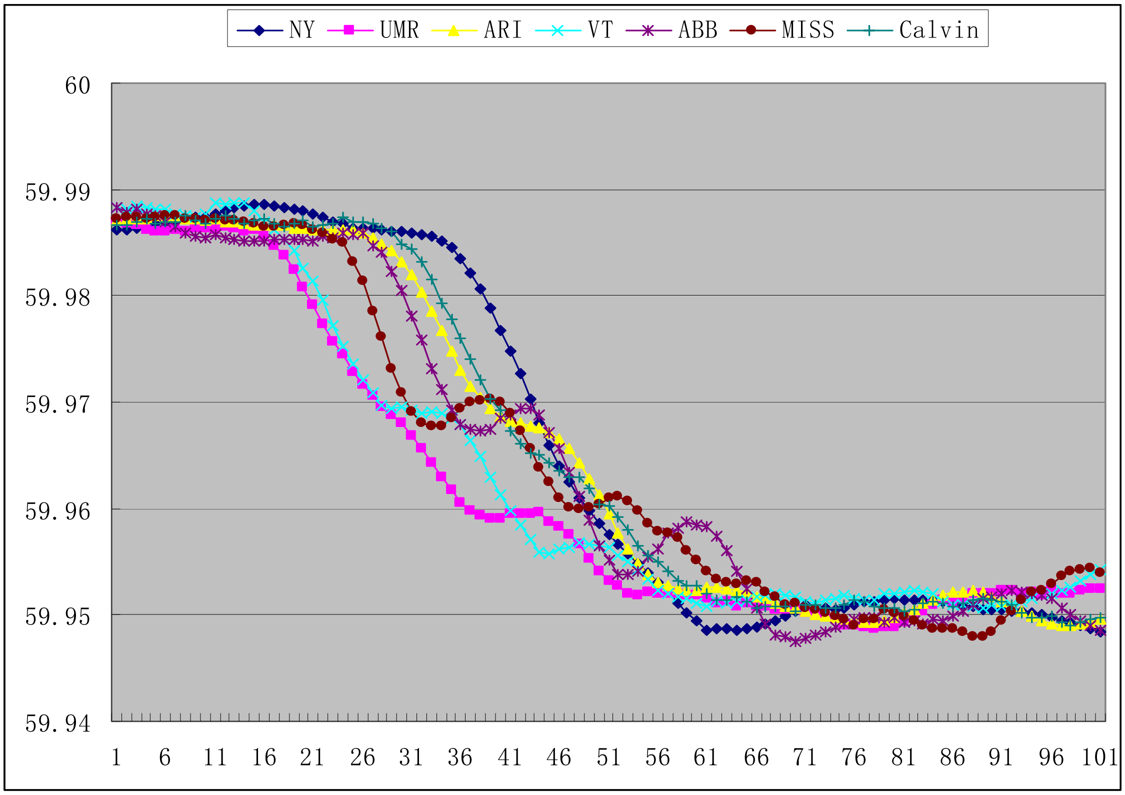



Figure 5.28 10-point average frequency of Sep. 19, 2004 event (10seconds)

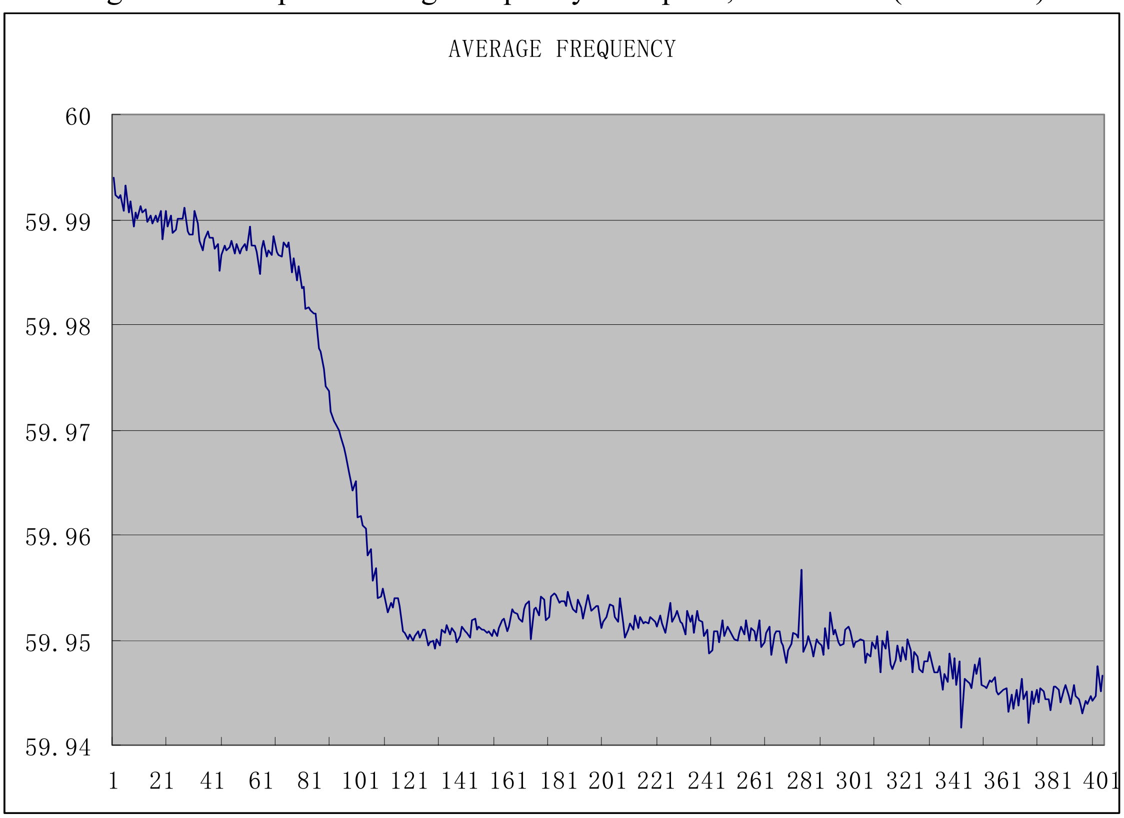



Figure 5.29 Average of frequency from FDR units of Sep. 19, 2004 event

Figure 5.29 is the average of frequency data of seven FDR units, which recorded this event. The frequency dropped to approximately 59.95Hz at 8:56:02. The amount of frequency change in this event can be calculated from this figure. In this case, average frequency change is 0.0374Hz, so estimated amount of tripped generation can be calculated from the empirical equation:

$$\Delta P = \Delta f \times \frac{dP}{df}_{EUS} = 0.0374 \times 31464 \approx 1178.1MW$$

while the actual tripped generation was around 1180MW, so the error of tripped generation estimation is:

$$\delta = (\Delta P_{real} - \Delta P) / \Delta P_{real} = \frac{1180 - 1178.1}{1180} \times 100\% = 0.153\%$$

From the average frequency data, frequency drop sequence of each FDR is: UMR, VT, MISS, ABB, ARI, Calvin, NY. From the delay time difference, the event location can be estimated as shown in Figure 5.30. Estimated triangulation shows the event should locate in the west area of Kentucky, and near Indiana and Illinois. The blue dot is the estimated event location, while the real event was located at the square on the left lower side.

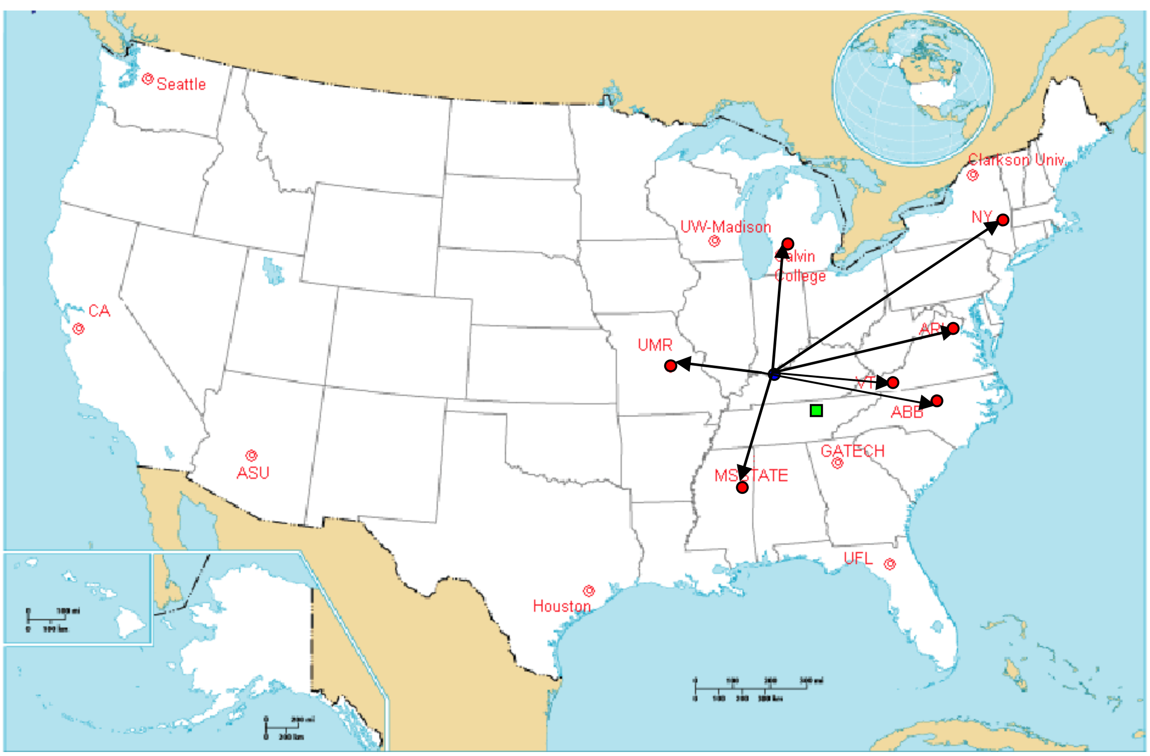


Figure 5.30 Triangulation of tripped generator location of Sep. 19, 2004 event

### 5.5.4 Fault Event of Generator Tripped on Nov.23, 2004

The last case occurred on Nov.23, 2004. The EUS System experienced a sudden frequency decline (Figure 5.31), and the FNET system recorded the frequency information at each of the FDR units. Figure 5.31 is raw frequency data during the event period, and the time range is 3 minutes including pre-event and post-event period. Figure 5.32 is the detailed frequency data, and the time range is 20 seconds.

Figure 5.33 is the 10-point average frequency data of each FDR. From the figures, it is very clear that before the event happened, the EUS system frequency was around 60Hz.

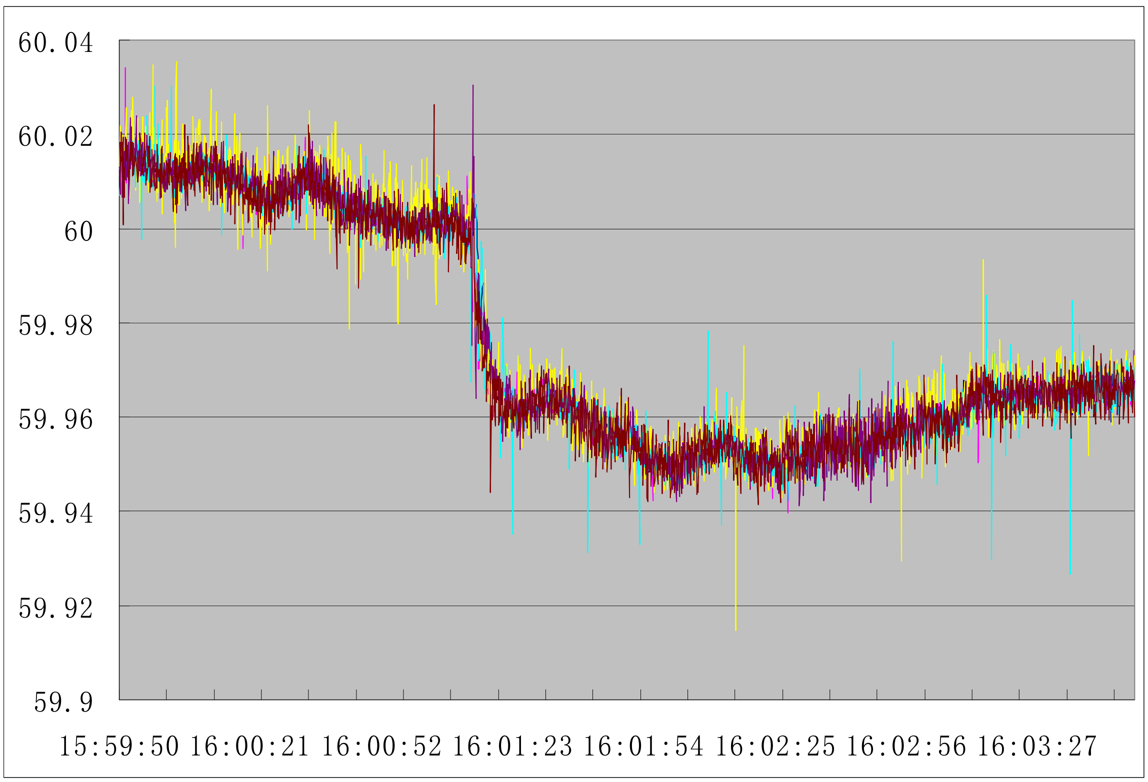



Figure 5.31 Raw frequency data of Nov. 23, 2004 event (3minutes)

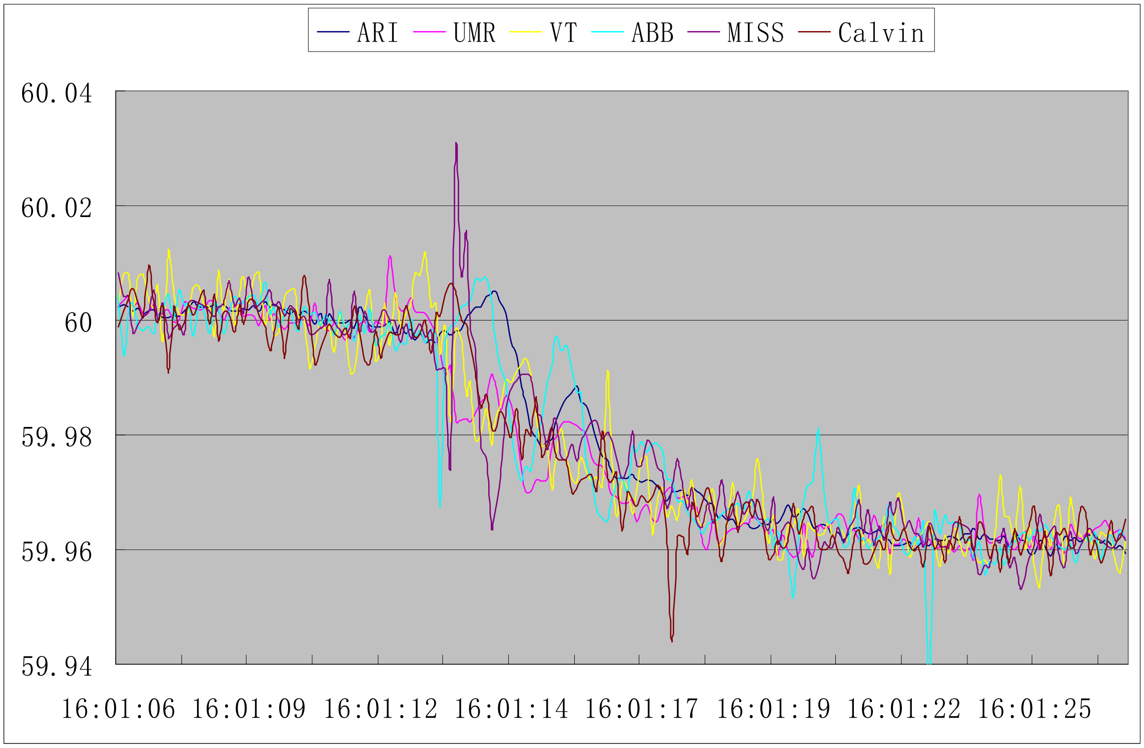



Figure 5.32 Detailed raw frequency data of Nov. 23, 2004 event (20seconds)

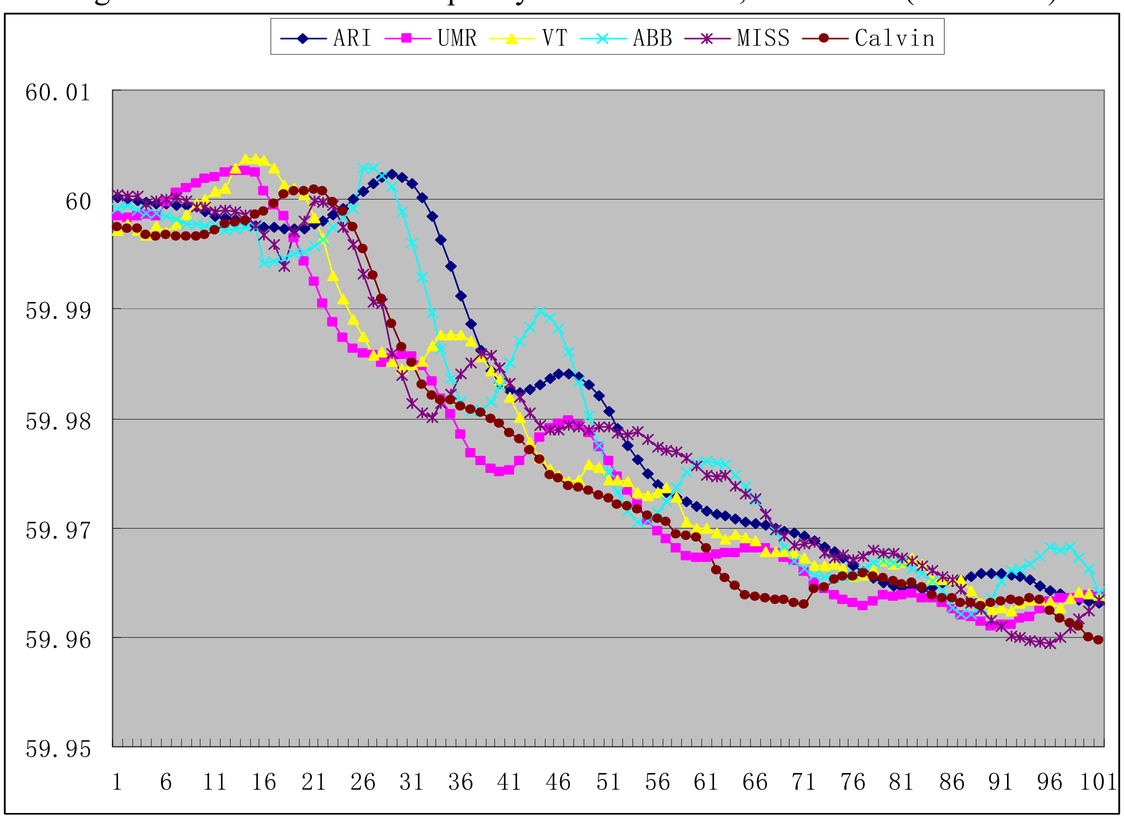



Figure 5.33 10-point average frequency of Nov. 23, 2004 event (10seconds)

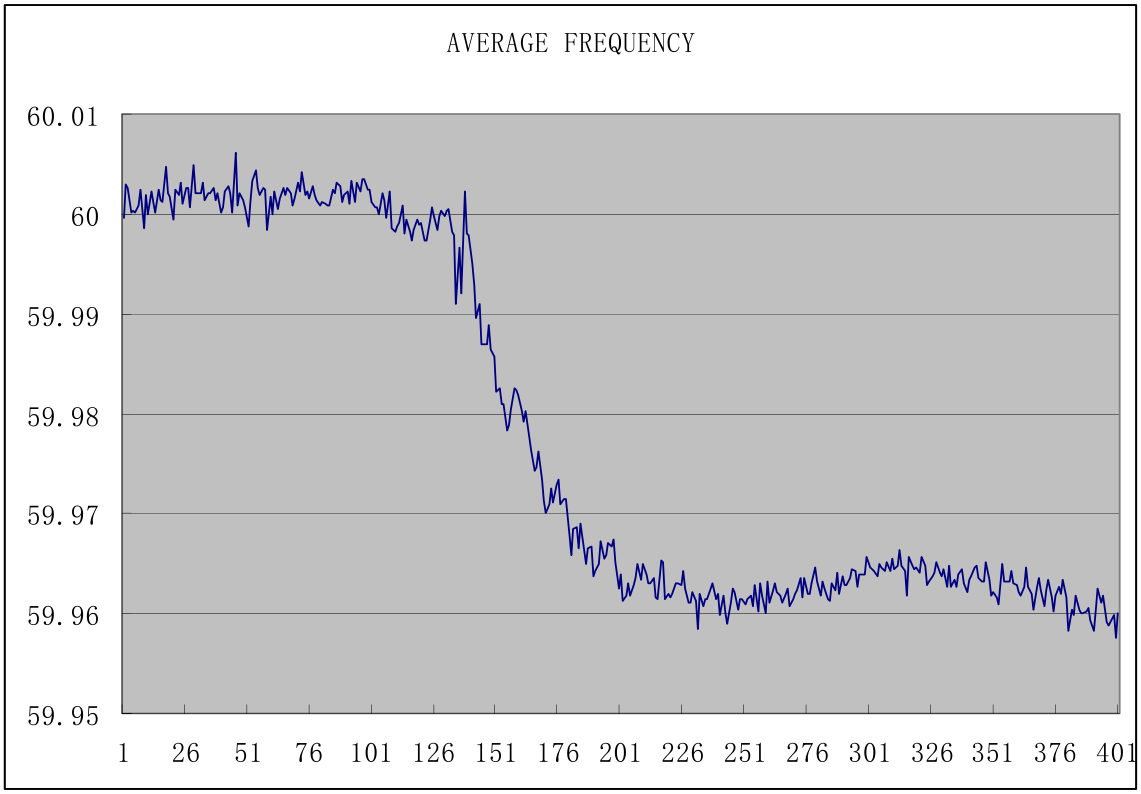



Figure 5.34 Average of frequency from 6 FDR units of Nov. 23, 2004 event

Figure 5.34 is the average of frequency data of six FDR units that recorded this event. The frequency dropped to approximately 59.961Hz at 16:01:19. The amount of frequency change in this event can be calculated from this figure. In this case, average frequency change is 0.0387Hz, so estimated amount of tripped generation can be calculated from the empirical equation:

$$\Delta P = \Delta f \times \frac{dP}{df}_{EUS} = 0.0387 \times 31464 \approx 1219MW$$

while the actual tripped generation was around 1190MW, so the error of tripped generation estimation is:

$$\delta = (\Delta P_{real} - \Delta P) / \Delta P_{real} = \frac{1190 - 1219}{1190} \times 100\% = -2.45\%$$

From the average frequency data, frequency drop sequence of each FDR is: UMR, VT, MISS, ABB, ARI, Calvin, NY. From the delay time difference, the event location can be estimated as shown in Figure 5.35. Estimated triangulation shows the event should locate in the joint area of Tennessee, Georgia and Alabama. The blue dot is the estimated event location, while the real event was located at the square on the left lower side.

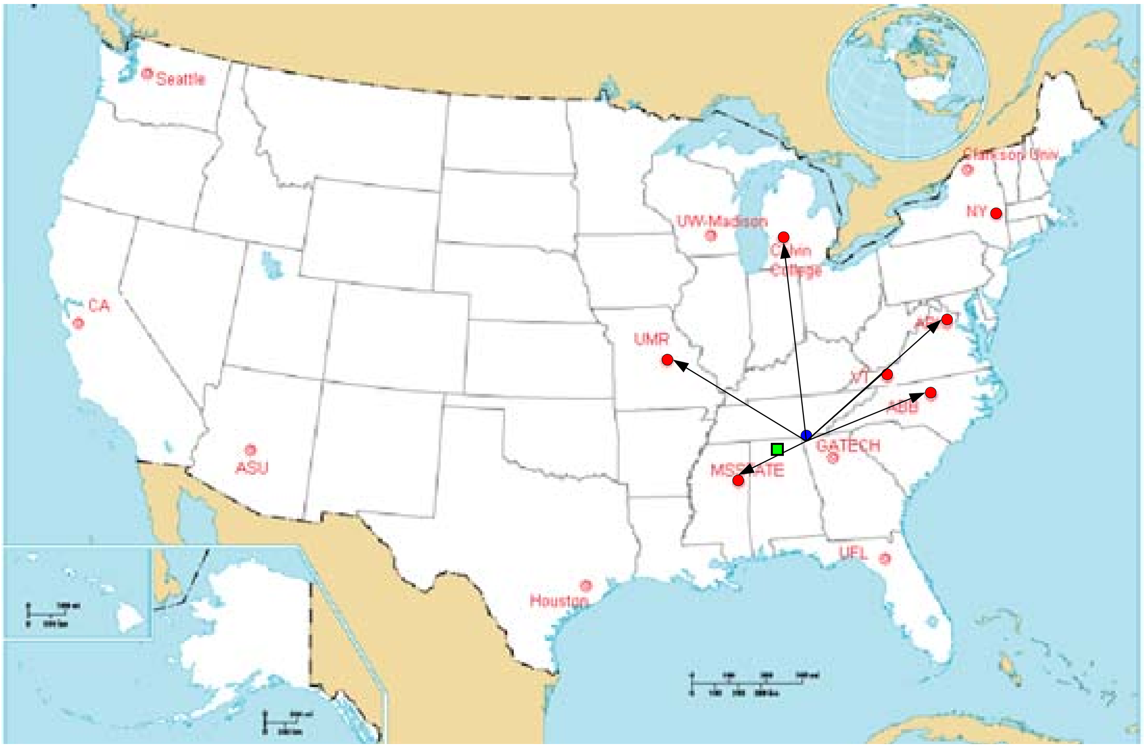



Figure 5.35 Triangulation of tripped generator location of Nov. 23, 2004 event

### 5.5.5 Summary of Fault Event Cases in EUS

Here in this report, there are four generator tripped events analyzed. After the analysis, the detailed information of these four events was reported to make a comparison with the estimated result. The location comparison results are listed in the TableTABLE 5.3, and the generation comparisons are listed in the Table TABLE 5.4.

Table 5.3 Location Comparison between the Estimated Location and Real Location

| Event Date | Time (GMT) | Estimated Location | Event Location |
|---|---|---|---|
| Aug.4, 2004 | 14:23:08 | Joint area of Michigan, Indiana and Ohio | Davis Besse (ECAR) |
| Aug.6, 2004 | 12:36:47 | Middle north area of Tennessee | Cumberland (TVA) |
| Sep.19,2004 | 08:55:57 | West area of Kentucky, and near Indiana and Illinois | WATTS BAR (TVA) |
| Nov.23, 2004 | 15:59:53 | Joint area of Tennessee, Georgia and Alabama | Browns Ferry (TVA) |

Table 5.4 Generation Comparison between Estimated Amount and Real Tripped Amount

| Date | Time(GMT) | Est. Tripped Gen. | Real Tripped Gen | Error |
|---|---|---|---|---|
| Aug.4, 2004 | 14:23:08 | 786.6 MW | 870 MW | 9.58% |
| Aug.6, 2004 | 12:36:47 | 1371.9 MW | 1300 MW | -5.53% |
| Sep.19,2004 | 08:55:57 | 1178.1 MW | 1180 MW | 0.153% |
| Nov.23, 2004 | 15:59:53 | 1219 MW | 1190 MW | -2.45% |

From the comparison, the empirical equation of tripped generation estimation has good accuracy, while the location estimation algorithm still needs to be improved. The error of tripped generation estimation is due to the accuracy of the coefficient of the empirical equation, and this coefficient is derived from the cases from WECC system. Now with the known cases from EUS system, the coefficient can be modified and improved and the accuracy of generation estimation can be better. The location estimation is based on the solution of n-dimension nonlinear differential equation, and the accuracy is affected by the speed of frequency propagation and the topology of transmission system. There is much room for enhancing the accuracy of location estimation.

### 5.5.6 PSS/E Simulation of EUS Cases

With the information of FNET, the post-disturbance scenario of the events in EUS System can be reconstructed with dynamic simulation software. The result of simulation can be used to compare with the analysis of real records of FNET. In order to simulate the events in PSS/E, the relative bus nodes of the generators where the event occurred should be picked up in raw data file (Table 5.5). In addition, the buses that represent FDR units should be listed in the raw data file (Table 5.6).

Table 5.5 Bus node Information of generator in events in PSS/E data

| | | |
|---|---|---|
| Event occurred date | 08/04/2004 | 09/19/2004 |
| Relative Bus Number | 21630 | 4197 |
| Bus name | 02DAV-BE | N1WBN |
| Bus location | Davis | Watts Bar Nuclear, TN |

Table 5.6 Bus Node Information of FDR Units in PSS/E data

| FDR name | Bus Num | Bus Volt(kV) | Bus Name | Bus Loc |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| NY | 78980 | 230 | ROTRDM.2 | Rotter Dam, NY |
| UMR | 96041 | 345 | 7FRANKS | Franks,MO |
| ARI | 14053 | 230 | 6JEFF ST | Jefferson ST.,VA |
| VT | 22567 | 345 | 05M FUNK | Matt Funk, VA |
| ABB | 11107 | 500 | 8PL GRDN | Pleasant Garden,NC |
| MISS | 35 | 500 | 8W POINT | West Point, MS |
| UFL | 44102 | 230 | PKRD | Parker Road, FL |
| Calvin | 28197 | 345 | 18ARGENT | Argenta, MI |

In the simulation, the scenario is created following the real system events. The generator is tripped to apply a fault in the system, and the frequency response at the selected FDR buses are recorded to be plotted for analysis. Figure 5.36 is the frequency plot of the FDR buses of UMR, ARI, VT, ABB, MISS, and UFL in Aug. 4, 2005 generator tripped event.

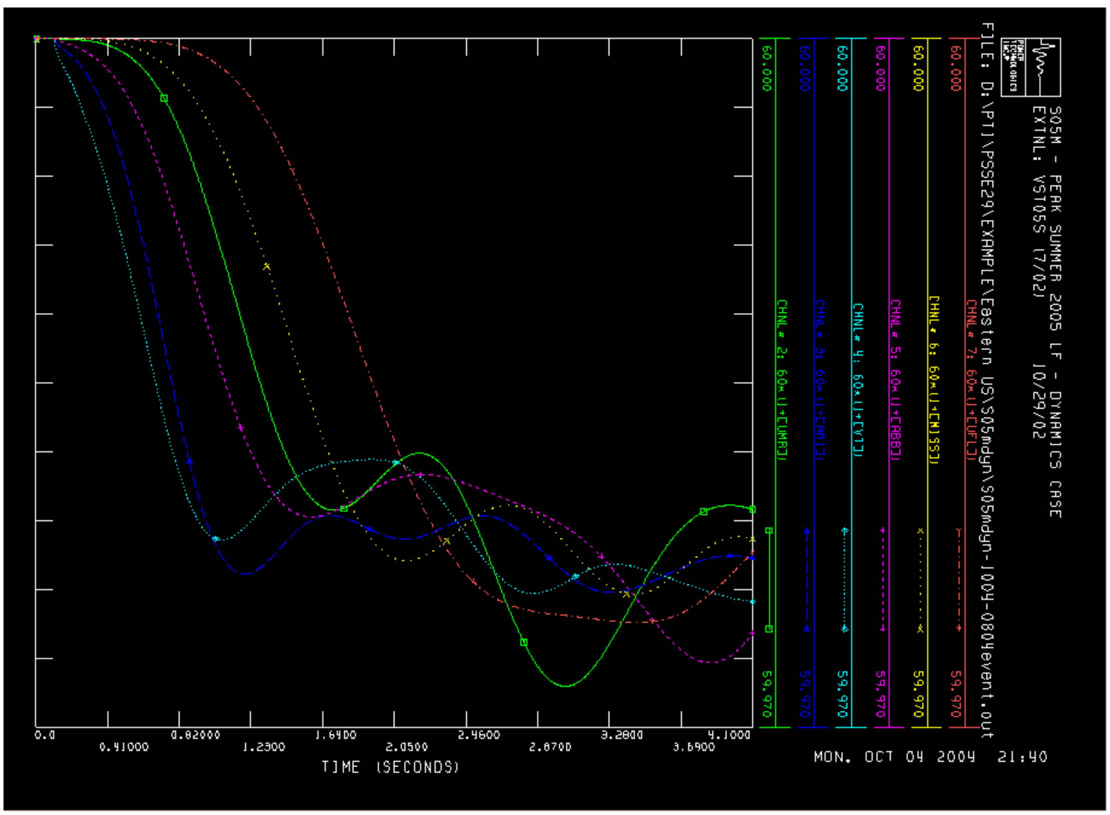



Figure 5.36 Frequency Response on Aug. 4 Event in PSS/E simulation

For the Aug. 4 event, the frequency response in FDR records and PSS/E simulation can be listed in the TableTABLE 5.7 to compare. The frequency response sequences of these two scenarios are almost the same except the FDR at UMR. The first swing of the frequency response of each observed bus is listed in the TableTABLE 5.8.

Table 5.7 Frequency response Comparison between Real Record and PSS/E Simulation in Aug.4 event

| FDR records | | | PSS/E results | | |
|---|---|---|---|---|---|
| Unit | Drop T | DiffT | Unit | Drop T | DiffT |
| VT | 2.7 | | VT | .35102 | |
| UMR | 3.2 | 0.5 | ARI | .48303 | .13021 |
| ABB | 3.3 | 0.1 | ABB | .67121 | .18818 |
| ARI | 3.8 | 0.5 | UMR | .87625 | .20504 |
| MISS | 4.5 | 0.7 | MISS | 1.0757 | .19945 |
| UFL | 4.5 | 0 | UFL | 1.4183 | 0.3426 |

Table 5.8 Bottom Freq Value of First Swing in Simulation Result in Aug. 4 event

| Unit | Time | Freq | Delta T | Delta F | df/dt |
|---|---|---|---|---|---|
| VT | 1.0616 | 59.978 | 0.71058 | -0.017 | -0.02392 |
| ARI | 1.1932 | 59.977 | 0.71017 | -0.018 | -0.02535 |
| ABB | 1.5727 | 59.979 | 0.90149 | -0.016 | -0.01775 |
| UMR | 1.6987 | 59.979 | 0.82245 | -0.016 | -0.01945 |
| MISS | 2.1071 | 59.977 | 1.0314 | -0.018 | -0.01745 |
| UFL | 2.6495 | 59.976 | 1.2312 | -0.019 | -0.01543 |

Figure 5.37 is the frequency plot of the FDR buses of NY, UMR, ARI, VT, ABB and MISS in Sep. 19 generator tripped event.

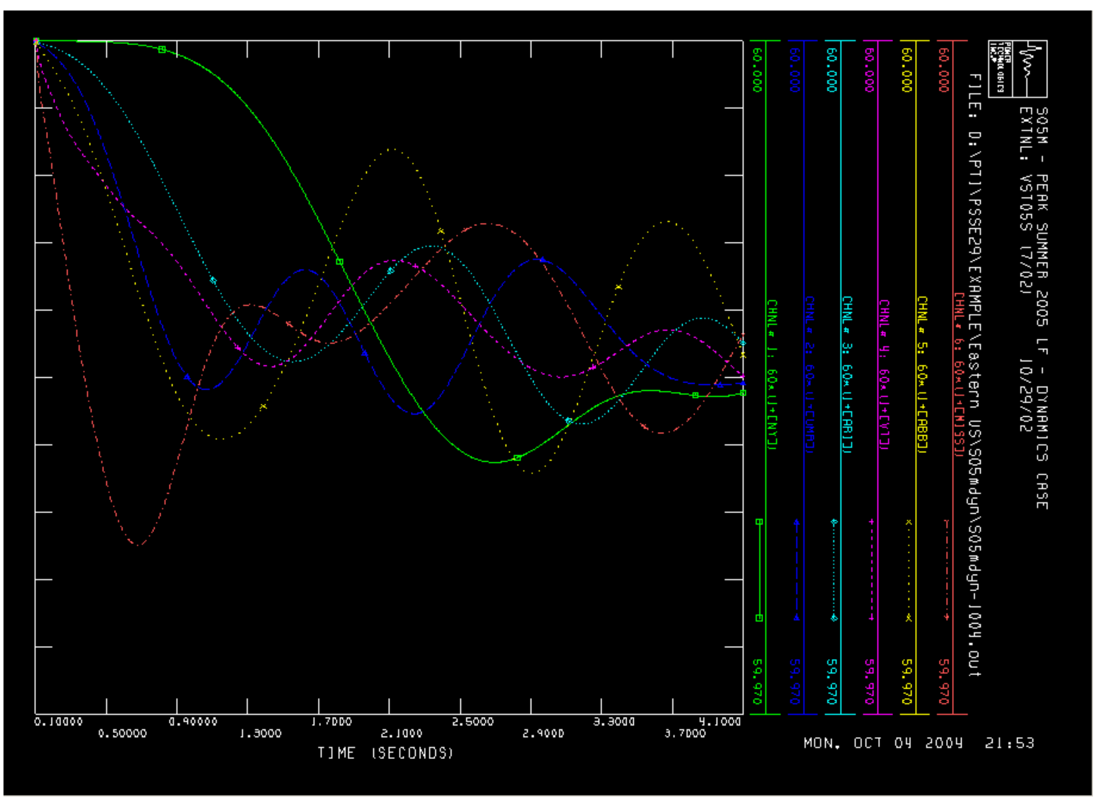



Figure 5.37 Frequency Response on Sep. 19 Event in PSS/E simulation

For the Sep. 19 event, the frequency response in FDR records and PSS/E simulation can be listed in the Table 5.9 to compare. The frequency response sequences of these two scenarios are almost the same except the FDR at UMR. The first swing of the frequency response of each observed bus is listed in

TABLE 5.10.

Table 5.9 Frequency response Comparison between Real Record and PSS/E Simulation in Sep. 19 event

| FDR records | | | PSS/E results | | |
|---|---|---|---|---|---|
| Unit | DropT | DiffT | Unit | DropT | DiffT |
| UMR | 2.6 | | MISS | .17799 | |
| VT | 2.8 | 0.2 | VT | .36337 | .18538 |
| MISS | 3.4 | 0.6 | ABB | .42516 | .06179 |
| ABB | 3.6 | 0.2 | UMR | .501 | .07584 |
| ARI | 3.7 | 0.1 | ARI | .73412 | .23312 |
| Calvin | 3.9 | 0.2 | Calvin | .83243 | .09831 |
| NY | 4.4 | 0.5 | NY | 1.4869 | .65447 |

Table 5.10 Bottom Freq Value of First Swing in Simulation Result in Sep. 19 event

| Unit | Time | Freq | Delta T | Delta F | df/dt |
|---|---|---|---|---|---|
| MISS | .67315 | 59.978 | 0.49516 | -0.017 | -0.03433 |
| VT | 1.4156 | 59.986 | 1.05223 | -0.009 | -0.00855 |
| ABB | 1.1592 | 59.982 | 0.73404 | -0.013 | -0.01771 |
| UMR | 1.0684 | 59.984 | 0.5674 | -0.011 | -0.01939 |
| ARI | 1.5812 | 59.986 | 0.84708 | -0.009 | -0.01062 |
| Calvin | 1.6613 | 59.985 | 0.82887 | -0.01 | -0.01206 |
| NY | 2.6922 | 59.981 | 1.2053 | -0.014 | -0.01162 |

With PSS/E simulation results, the triangulation of event location can be modified, the new locations of event shown in Figure 5.38 and Figure 5.39.

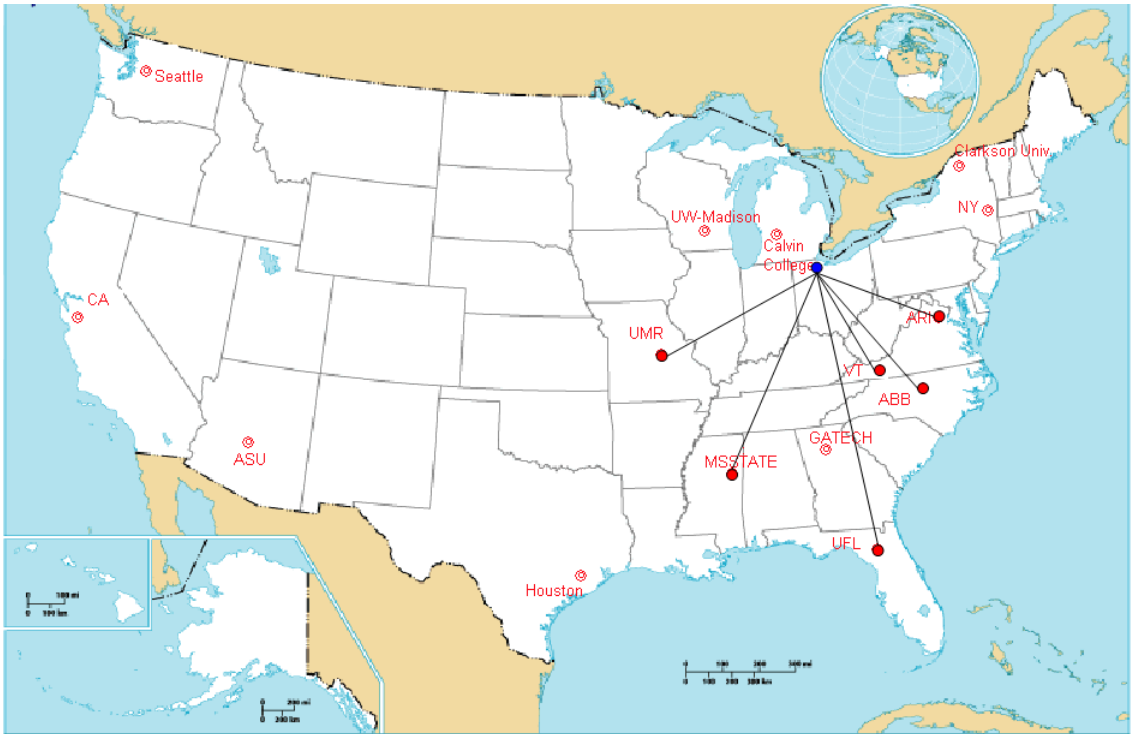



Figure 5.38 PSS/E result estimated event location of Aug. 4 event

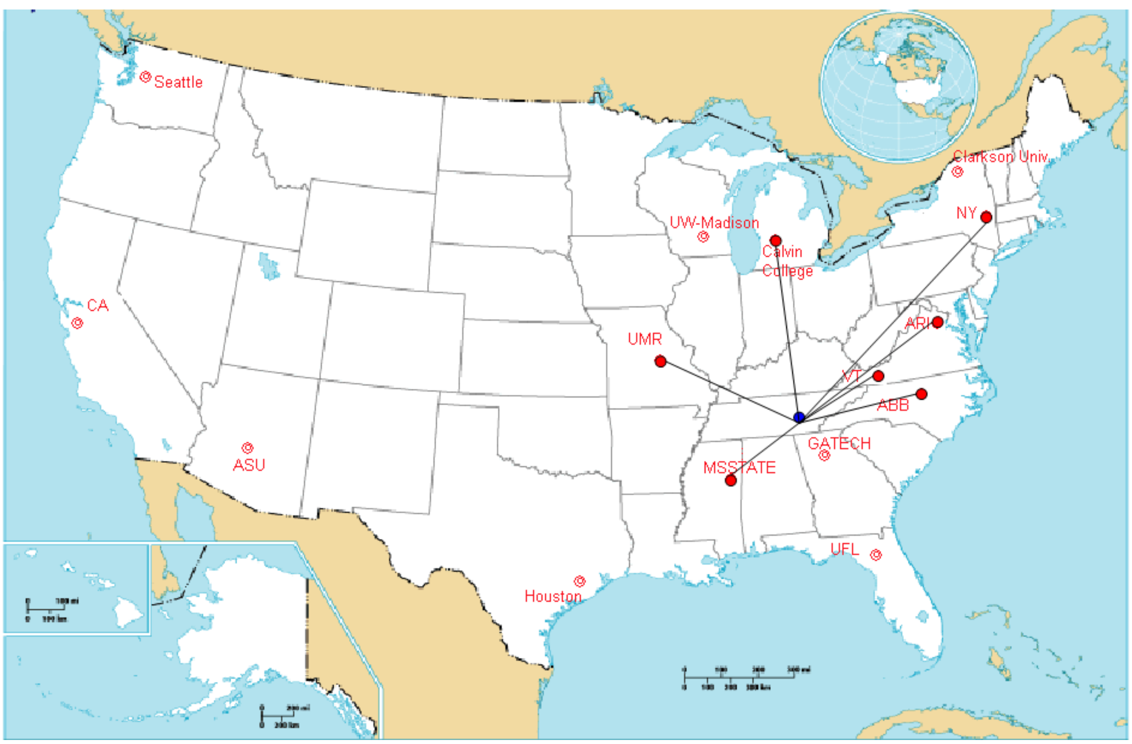



Figure 5.39 PSS/E result estimated event location of Sep. 19 event

## 5.6 Summary

In this chapter, the frequency disturbance analysis is addressed, and the frequency trigger is designed to detect the significant frequency fluctuation in each interconnection. The location of the disturbance can be estimated by the pattern of frequency drop delay with the triangulation technique and TDOA method, the algorithm is designed to analyze the known cases, and the result shows the estimation is relatively good enough. The further estimation is introduced to get location that is more detailed. Using the empirical equations, changed generation in the disturbance can be estimated with good accuracy. Some example cases are provided to show how to use FNET to monitor and analyze power system disturbance.

# Chapter 6 Under Frequency Load Shedding Based on Wide Area Information

## 6.1 Introduction

In power system, it is well known that large severe disturbances such as generator tripping or load outages can initiate cascading outages, system separation into islands, and even the complete breakup. Under frequency load shedding takes place during the beginning phase of a dynamic change of the system frequency initiated by these disturbances [73].

Under frequency load shedding is a common practice for electric power utilities in order to prevent frequency drop in power systems after disturbances causing dangerous imbalance between the load and generation [74]. A sudden loss of generation causes frequency to fall as the residual generating capacity no longer matches the connected system load. If a considerable amount of generation were lost, the only effective way of correcting the imbalance would be quickly shed loads before frequency falls so low that the power system collapse. Utilities would only resort to load shedding as a final measure and this action has the advantage of disconnecting selected loads for a relatively short period, rather than interrupting all consumers for extended periods. The required approach for load shedding can best be explained by examining the reduction of frequency on loss of generation on the power system, for about two seconds, the period when there is no response to the action of turbo-governor controls, the frequency falls at a fast rate and reaches a minimum level. Subsequently, as turbine outputs respond to governor controls, there is a recovery of frequency to a steady, but reduced level. In addition, effective load shedding scheme must make provision for both minimum and the residual frequency [75].

The traditional load shedding relays shed load in several steps with the preset tripping frequency and pre-designated feeders derived from assumed system conditions and load distributions, this kind of preset setting point and some other parameters will be given to the relays. When the frequency of the relay reduces to the setting point, the relay acts to shedding the preset proportion of the load connects to it. If the frequency still goes down, it will go to the second step and so on. Some relays are set in 4 steps or 6 steps. In this means, load shedding relays can reduce power mismatches in systems deficient in generation gradually and make the system frequency recovery to normal level. However, the problem is that all these setting points are preselected and based on simulation result and operators' experience; they cannot meet the requirement of all kinds of disturbance. The traditional scheme is a one-size-fits-all compromise of different operation scenarios. Nowadays the existing plans are predominantly deterministic, not taking into account the actual system state and topology, operating time point and the nature and the magnitude of the disturbance. Therefore, it will inevitably result in either over or under shed as it cannot adapt to the continuous changes in system conditions [76].

The other major drawbacks of conventional solutions are that local protection devices are not considering a system view and are therefore not able to take optimized and coordinated actions. Even in the case of under-frequency controlled load or generation shedding, the frequency itself is system information, but the actions are locally taken on predefined design rules. A system view would come into account for example if the set values for the shedding devices were updated according to the actual system status.

There is a need to make the UFLS system to be most effective, this need the location and magnitude of all generation and loads. In an under frequency emergency, both generation and load profiles are constantly changing yet under frequency relays have only a single set point for all scenarios. A need exists to develop an adaptive UFLS system that can customize under frequency relay set points dynamically in response to any system condition.

This task can be achieved in stages. First, new knowledge from FNET historical measurement records can help better understand overall system frequency patterns and improve load-frequency modeling accuracy, which will help validate simulation results that are used to design control strategies and load shedding schemes. Later, with better communication capability, advanced load-shedding schemes can be used to shed load based on estimated generation imbalance and trip location using real-time FNET data. Global intelligent control strategies will replace local under frequency relay actions that are made without the knowledge of the system overall behavior.

Since frequency disturbances propagate as electromechanical waves, rather than passively waiting for local under-frequency relays to shed load in steps, with FNET information, pro-active approach and overall coordination should be possible to achieve faster system recovery.

## 6.2 Design the Adaptive UFLS Scheme Based on FNET

Since frequency disturbances propagate as electromechanical waves, rather than passively waiting for local under-frequency relays to shed load in steps, with FNET information, pro-active approach and overall coordination should be possible to achieve faster system recovery. Here, FNET may help identify the location of the disturbance and predict the amount of the generation-load unbalance at a very early stage.

When there is a disturbance occurs in the power grid, the agents (FDR) can catch the information and send to the control center, and at the same time suppose the relays know the frequencies of all other relays, and receive the relative setting configuration information according to this disturbance, so that the relays can respond to this particular case. In this means, UFLS system can dynamically customize load-shedding relays setting points in response to any system condition. With this information of all over the power grid, the load shedding relays can be set for different cases to meet the demand of different system faults. This means that each of these digital relays has its own thread of local control, and they can also perceive a more global scope of the system and act in response to their non-local environment by communicating with other relays via LANs or WANs.

Here, FNET could help identify the location of the disturbance and predict the amount of the generation-load unbalance at a very early stage. Several major considerations in designing an advanced wide area UFLS scheme are given below:

- Estimate disturbance magnitude and the required amount of load to be shed
- Estimate of the location of disturbance
- Determine the distribution of the loads to be shed
- Select optimum shedding times

Before the designation, there are some assumptions need to be declared first:

- The system inertia constant and structure are assumed to be known
- Each local relay is assumed to know the frequency of the whole system
- The relay's parameters can be modified dynamically
- The system structure is assumed to be known

### 6.2.1 Amount of Unbalanced Power

The main results from the UFLS point of view, given in [77] in the closed form, are:

1. The initial rate of frequency change $df/dt$ is proportional to the power imbalance $\Delta p$, and it also depends on the electric power system inertia
2. The values of the minimum frequency $f_{\min}$ and the new steady-state frequency $f_{ss}$ reached during the following transient process are proportional to the power imbalance $\Delta p$ and depend on the dynamic properties of turbines, governors, loads and other control devices.

From the above result, we can write [78]:

$$\frac{d\varpi_i}{dt} = \frac{\Delta P_{mi} - \Delta P_{ei}}{M_i} = \frac{\Delta P_{di}}{M_i}$$

here, $M = 2H$

$$P_{msystem} = \sum_{i=1}^{N} P_{mi} \text{ , } P_{esystem} = \sum_{i=1}^{N} P_{ei}$$

$$\Delta P_d = P_{msystem} - P_{esystem} = 2\frac{d\varpi}{dt}H_{system}$$

From the above analysis, conclusion can be drawn that the real-time frequency and the rate of change of frequency $df/dt$ of the whole system are the most important parameters in calculation or estimation of the imbalance between load and generation. So there are many frequency estimation or predict algorithm to get these two parameters. Now, with the help of wide-area measurement (PMU and FDR), the frequency and the rate of change of frequency can be easily measured and provided for this application, which means the rate can be calculated using the initial samples after the disturbance of the generators' electrical angular velocities at intervals of a constant time interval, and the $H_{system}$ is the sum of all generators' inertia constants. So the amount of imbalance active power $\Delta p$ can be calculated in the central server of FNET. Actually, in section 5.4, the tripped generation in disturbance is discussed and the estimation method of the empirical equation is given. So this parameter can be calculated thru that way.

The time constants describing the frequency changes and electromechanical transient processes occurring in huge interconnected power system are comparatively big (0.1~5 seconds), so the speed of data transmission through the system to the control center server is not very critical. From the practical application point of view, additional time delays caused by the computation required for the control action derivation and its distribution and transmission to loads, as well as delay caused by circuit breaker action, should be less than the intentional time delay of UFLS (e.g. 0.3 s).

### 6.2.2 Location of Disturbance

There is few paper mentioned this problem, because it is always included in the problem of where to shed the load? Reference [74] tries to use the voltage reduction and the elasticity factor of ties to find out in which area the power lost. The present evolution of interconnected power systems has ties between utilities that are small in relation to each utility's load and generation capacity. The consequent elasticity of the ties has introduced a new factor, that there will be a different rate of initial frequency reduction in adjoining utilities following the loss of generation. This can be seen by the reduction of frequency, after there has been a loss of generation in one area of a two-area network similar. In the area where the generators have been lost, frequency falls immediately. By contrast, in the undisturbed area, the frequency reduction is delayed. With conventional ULFS, loads would be shed in both areas with a delay of some 1.5 seconds before any load shedding could occur in the undisturbed area. Consequently, the mismatch between load and generation would persist for longer than may have been envisaged, so compounding the severity of the disturbance. The frequency response, shown in Figure 6.1 shows the advantages of concentrating load shedding in the area where generation had been lost. This is the particular feature, which differentiates the proposed new scheme from existing UFLS.

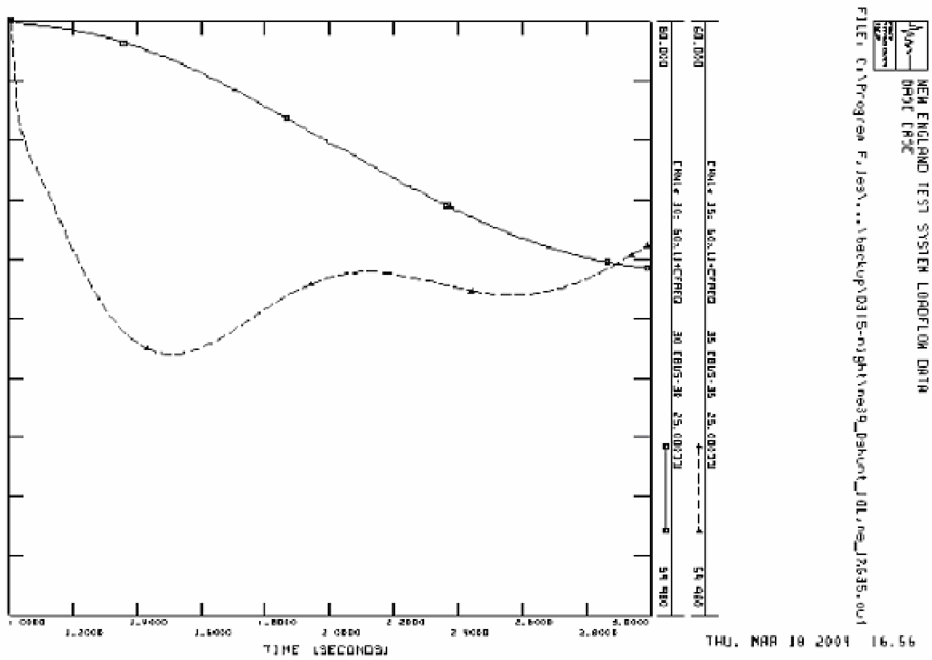



Figure 6.1 Frequency response of generator without governor action

From the figure above, it is very clear that the initial rate of frequencies decline is different between the generators and the generators that are near the disturbance area will drop much faster than those generators faraway from the disturbance. This future also depends on the inertia constant of the generator. The larger the inertia constant is, the slower the frequency drops. Because the information of the initial rate of each generator can be obtained based on wide area measurement, the location of disturbance can be easily find out in the system for the following design step of UFLS scheme.

### 6.2.3 Distribution of the Power between Possible Load Bus

This session try to discuss the distribution of control action throughout the power system. The traditional under-frequency load shedding only use setting point or setting rate, when the frequency or the rate of change of frequency reach the setting value, the relay reacts. As a result of frequency decline propagation, the relay near the bus of lost generation will first react to shed some load; while the relay far away from the bus can only delay the shedding action when the frequency decline propagate to this relay. This method is useful for the isolated power system, because the isolated power system is not large enough to cause the difference of frequency decline propagation. The isolated system is always very coherent in frequency, so the frequency at each relay is similar to each other. Thus the setting point can determine where to shed load first and where later.

The first original feature of the proposal is the concentration of load shedding to just the area surrounding the lost generators. The area can be identified within cycles of the generation loss (with no need for computer evaluations) by the initial voltage reductions at substations within the area. Although the voltage dips would only last a short time, the minimum voltage levels would be recorded. The allocation of load shedding at each of the identified substations would be in proportion to the voltage reduction so that the amount of load to be shed at substation (node) i, ( $\Delta p$ ), can be evaluated as [74]:

$$\Delta P_i = \frac{\Delta V_i \cdot \partial Q_i / \partial V_i}{\sum_{j=1}^{N} \left( \Delta V_j \cdot \partial Q_j / \partial V_j \right)} \cdot \Delta P_G$$

Where $\Delta V_i$ is voltage reduction at node i, $\partial Q_i / \partial V_i$ is the sensitivity of voltage at node i to change of reactive power, N is the total number of load nodes with significant voltage reduction and $\sum P_{LS}$ is given by equation.

Nowadays, the large-scale interconnected power system is becoming more and more related to each other. The tie lines can transmit more power than before, thus the system can be divided into several power sending areas (generation center) and power receiving areas (load center). When the loss of generation occurs in power sending areas, it is not clear that whether shed the load in which area can be more efficient for system frequency recovery and system stability. This problem is just because load shedding does not account for shortly active power flow in the system. For example, we can consider areas with export and import of energy. When power deficiency occurs, load shedding is demanded in the area that imports energy, but if it occurs in the area that exports energy, import increases, which can aggravate overloading of the interconnections and cause further cascading. Cascading can cause separation of the import area from the rest of the system. The import area can experience frequency and voltage collapse if there is no help from the rest of the system. The traditional under-frequency load shedding scheme is designed about 50 years ago. Although there are many adaptive schemes to make it more efficient, it still has limitation when it is used in multi-area large interconnected power system nowadays

Therefore, here a new method is brought out to solve this problem, the amount of load to be shed at substation (node) j, $\Delta p_j$, can be evaluated as

$$\Delta p_j = \frac{\Delta f_j \times p_{Lj}}{\sum_{j=1}^{m} \Delta f_j \times p_{Lj}} \times \Delta P_L$$

here, $\Delta P_L$ is the total required amount of load needed to be shed, $\Delta p_j$ is the amount of shedding load at each load bus, $p_{Lj}$ is the amount of original power of each load bus. So if a bus with heavy load and a large frequency deviation, it will cover a large part of shedding load amount.

### 6.2.4 Optimal Shedding Time Selection

This session try to discuss the exact shedding action time of relay. The shedding time is very critical in load shedding. If the shedding time is not match the demand of the system, the frequency cannot be recovered to normal frequency, sometimes over shedding or under shedding. The traditional relay can only be set at a frequency point or rate of change of frequency point, when the relative parameter reaches the setting point, the relay will react and shed the setting proportion load.

When a disturbance of frequency occurs in the system, some heavy load located at the node far away from the disturbance node, so the frequency decline propagation can not reach these loads relay in time, and some small load near the disturbance node may be shed first, but the frequency can not recovered, and the heavy load will finally be shed. This will cause over shedding problem. When the relays get the system status information from wide-area measurement system, the shedding time can be arranged more efficiently. In the aspect of whole system, when the control center find there is a disturbance in the system, the frequency setting point of load center can be set at a higher value so that these loads can be shed at a more early time.

The typical operating time with solid-state relays is in the range of 0.1 to 0.2 second, so the load shedding relays can get dynamically information form the system, and get the optimize setting frequency level and delay time, and it's enough for relays to act to cut the related load out of the system.

## 6.3 Scenario Analysis of New England 39-bus System

The simulation analysis makes use of New England 39-bus 10-gennerator system, shown in Figure 6.2, with some modification. The first system modification made was to enhance some transmission lines' impedance to separate the system into a 3-area system because the original system is a coherent system and all generators are in one cluster in instability status. Then the shunt of the system was modified to a normal level, so that the power flow in the system is almost just between the generators and loads.

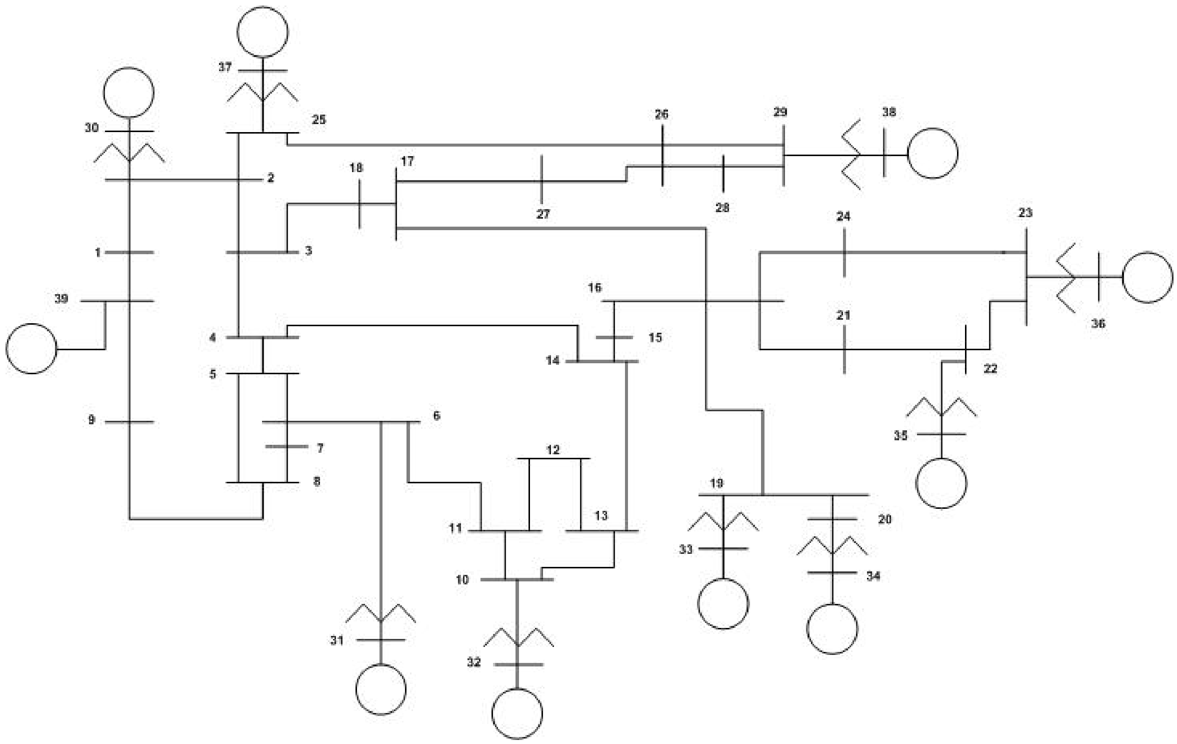



Figure 6.2 New England 39-bus power system

## 6.3.1 Simulation System Structure

In order to separate the system into three areas, four transmission lines' parameters need to be changed as 10 times the original value. These four lines are:

- 1~39 ×10
- 3~4 ×10
- 15~16 ×10
- 16~17 ×10

From the frequency curve, the generator 33/34/35/36 is in a group, 30/37/38 is in a group, 31/32 is in a group, 39 runs independently. So we can get a 3-area system shown in the following Figure 6.3. The generators of 30, 37 and 38 are in Area-I, 31, 32, 39 are in Area-II, the other 4 generators are in Area-III.

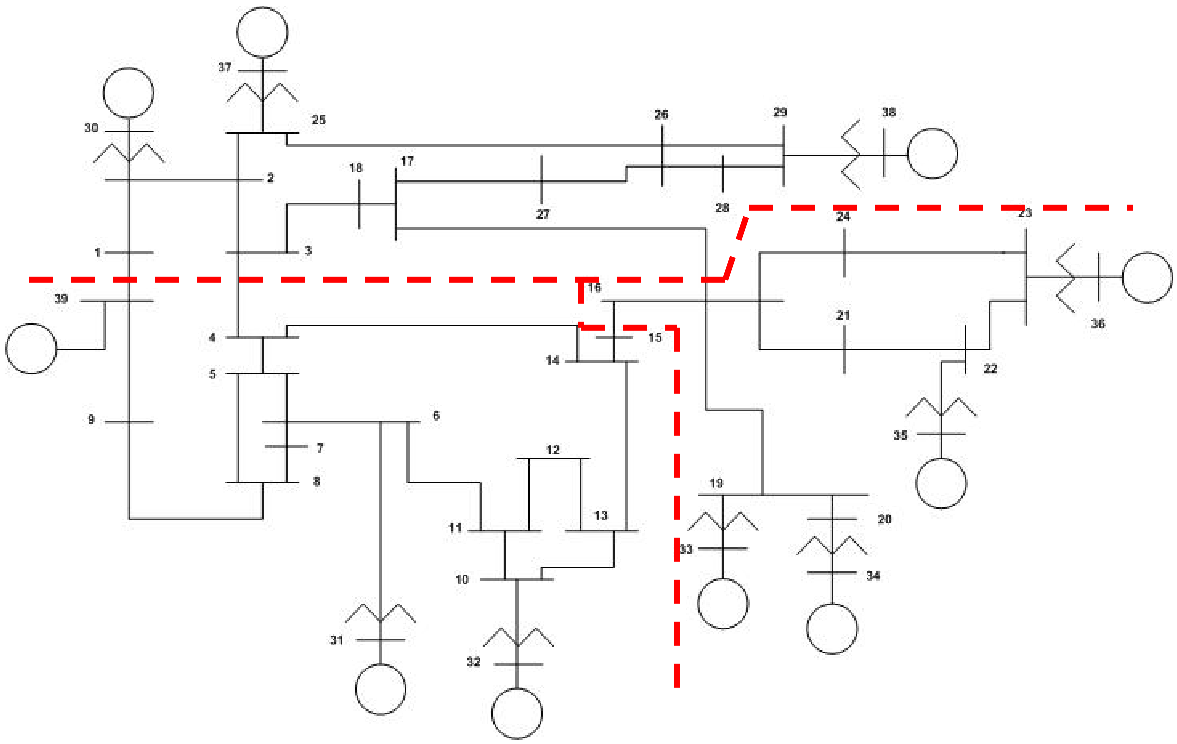



Figure 6.3 New England 39-bus power system in 3-area

Here the tables list the parameters of generators, loads and the power flow between the three areas after changing the impedance of transmission line.

Table 6.1 Generator Active and Reactive Power Generation

| Generator | P(MW) | Q(Mvar) |
|---|---|---|
| G30 | 250 | 175.8 |
| G31 | 541.7 | 189.2 |
| G32 | 650 | 182.1 |
| G33 | 632 | 57 |
| G34 | 508 | 142.8 |
| G35 | 650 | 241.1 |
| G36 | 560 | 203 |
| G37 | 540 | 20.8 |
| G38 | 830 | 49.5 |
| G39 | 1000 | 149.4 |

Table 6.2 Load Information in Simulation

| Bus | P(MW) | Q(Mvar) |
|---|---|---|
| 3 | 322 | 2.4 |
| 4 | 500 | 184 |
| 7 | 233.8 | 84 |
| 8 | 522 | 176 |
| 12 | 7.5 | 88 |

| | | |
|---|---|---|
| 15 | 320 | 153 |
| 16 | 329 | 32.3 |
| 18 | 158 | 30 |
| 20 | 628 | 103 |
| 21 | 274 | 115 |
| 23 | 247.5 | 84.6 |
| 24 | 308.6 | -92.2 |
| 25 | 224 | 47.2 |
| 26 | 139 | 17 |
| 27 | 281 | 75.5 |
| 28 | 206 | 27.6 |
| 29 | 283.5 | 26.9 |
| 31 | 9.2 | 4.6 |
| 39 | 1104 | 250 |

Table 6.3 Three Areas Power Flow Information

| Area | | GP(MW) | GQ(MVAR) | LP(MW) | LQ(MVAR) |
|---|---|---|---|---|---|
| 1 | 30/37/38 | 1620 | 246.1 | 1613.5 | 226.6 |
| | 3/18/25/26/27/28/29 | | | | |
| 2 | 31/32/39 | 2191.7 | 520.7 | 2696.5 | 939.6 |
| | 4/7/8/12/15/31/39 | | | | |
| 3 | 33/34/35/36 | 2350 | 643.9 | 1787.1 | 242.7 |
| | 16/20/21/23/24 | | | | |
| Total | | 6161.7 | 1410.7 | 6097.1 | 1408.9 |

Table 6.4 Power Flow of the four tie lines

| Branch | P (MW) | Q (MVAR) |
|---|---|---|
| 1->39(I->II) | 99.8 | -18.4 |
| 3->4(I->II) | 113.3 | 177.5 |
| 16->15(III->II) | 317.3 | 169.1 |
| 16->17(III->I) | 227.6 | -47.5 |

The simulation is running in PSS/E, with the network structure in raw file and dynamic parameters in .dyr file. The simulation used the modified 3-area system, and run different scenario to get the frequency response when there is no UFLS scheme, traditional UFLS scheme, adaptive dynamically UFLS scheme.

The disturbance is create by tripping each generator, then the program will give the response of frequency at each bus, at this time feed these frequencies into the algorithm of calculation and get the result of total shedding load amount, the amount at each load bus. With this information, the setting frequency and proportion can be get and feed into the PSS/E program. Thus, the system can get the frequency response of each case.

### 6.3.2 Analysis of the Bus33 Generator Trip Case

This is an example of these simulation cases. In this case, the fault is to trip the Generator 33 at time of 1 second. First, the simulation is running without any UFLS scheme, and the response of frequencies shown in Figure 6.4.

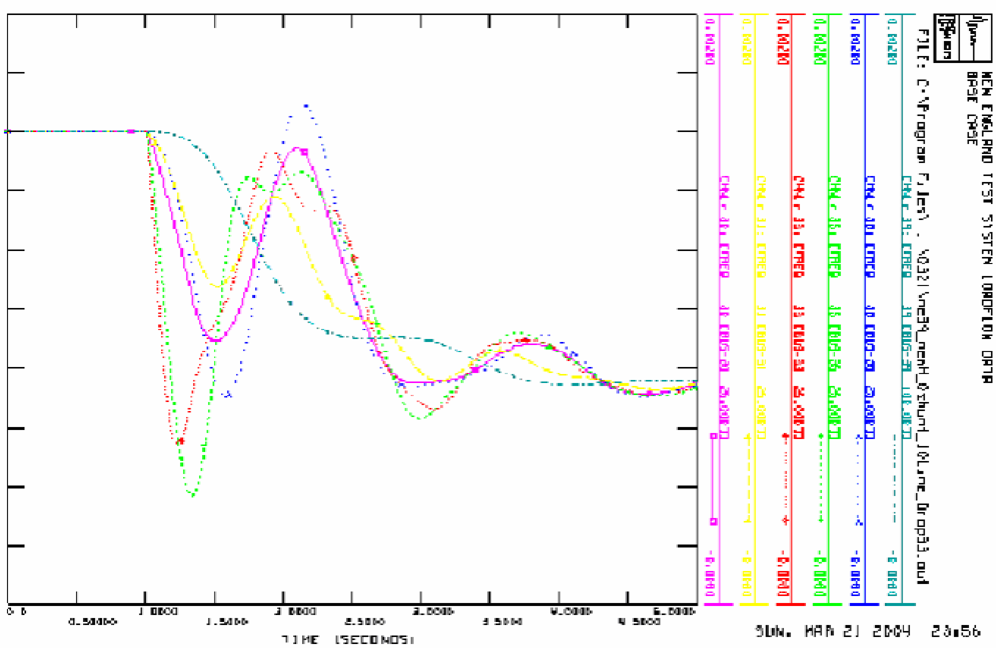



Figure 6.4 Frequency response of Gen 30, 31, 33, 35, 38, 39

Then employ the traditional UFLS scheme into the simulation. The UFLS relay set as:

3,18,23,24,25,26,29,
'LDSHBL',1, 59.7, 0.1, 0.1, 59.7, 0.1, 0.159, 59.6, 0.1, 0.165, 0.1/
4,7,8,12,15,16,20,21,27,28,31,39,
'LDSHBL',1, 59.8, 0.1, 0.1, 59.7, 0.1, 0.159, 59.6, 0.1, 0.165, 0.1/

Repeat the simulation, and get the response shown in Figure 6.5

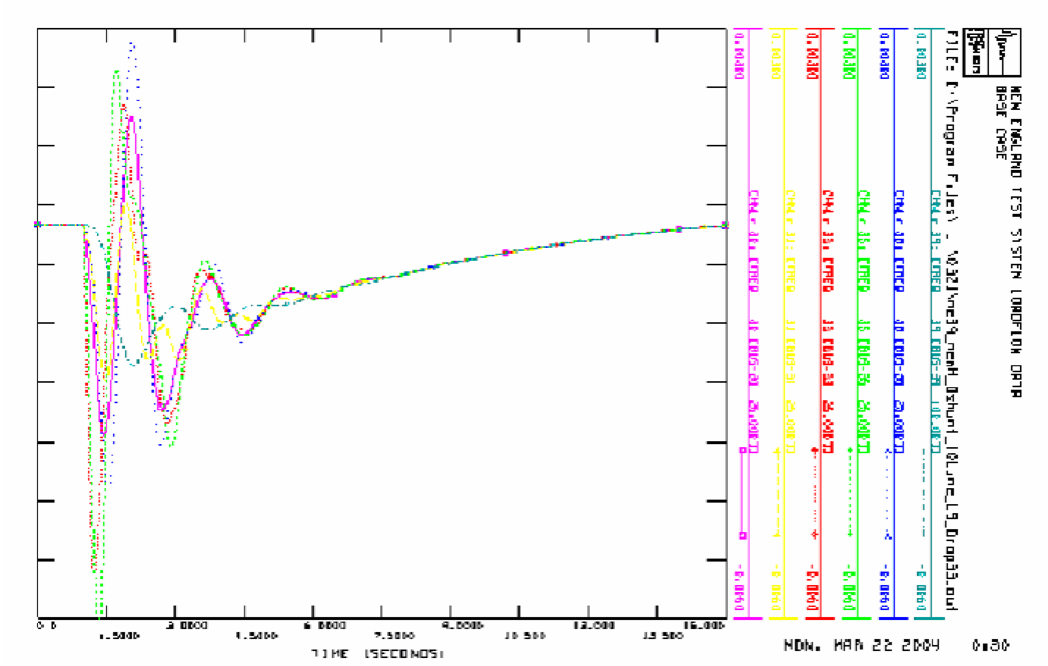


Figure 6.5 Frequency response of Gen 30, 31, 33, 35, 38, 39

In traditional UFLS scheme, the total amount of shedding load is 351.22MW, and this cause over-shedding and the system frequency increase above 60Hz. Now, employ the adaptive UFLS scheme in the simulation. The relays should be set as:

3 , 4, 7, 8, 12, 20, 25, 26, 27, 28, 29, 31, 39

'LDSHBL',1, 59.7, 0.1, 0.1, 59.6, 0.1, 0.15, 59.5, 0.1, 0.16, 0.1/

15, 16, 18

'LDSHBL',1, 59.8, 0.1, 0.1, 59.7, 0.1, 0.15, 59.5, 0.1, 0.16, 0.1/

21, 23, 24

'LDSHBL',1, 59.8, 0.1, 0.15, 59.7, 0.1, 0.15, 59.5, 0.1, 0.16, 0.1/

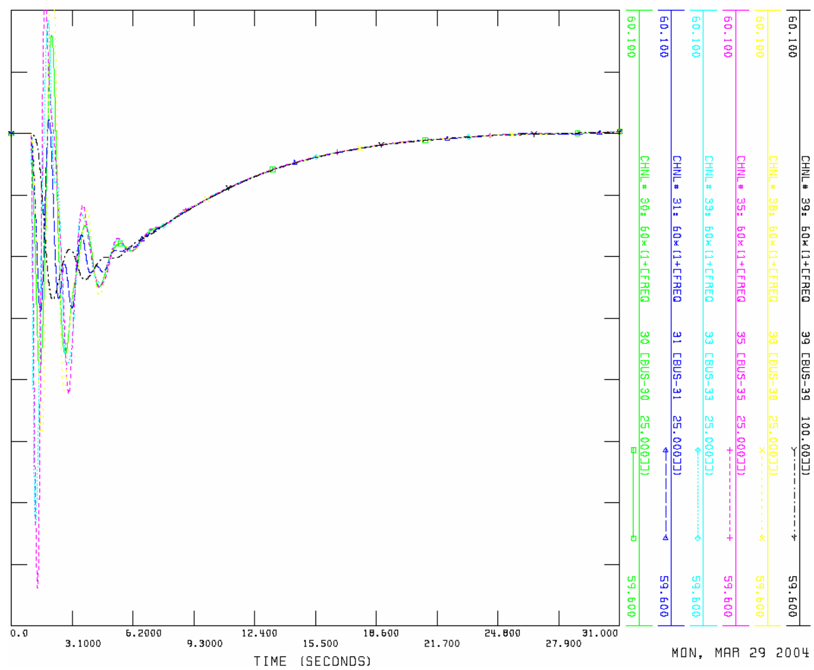



Figure 6.6 Adaptive UFLS scheme, frequency response of Gen 30, 31, 33, 35, 38, 39

Table 6.5 Shedding Load Information in Case of Drop33

| Trip Gen | Shed Location Bus | Shed Time Start at 1 s | Shed Load P(MW) | Shed Load Q(MVAR) | Shed Freq (Hz) |
|---|---|---|---|---|---|
| 33 (632MW) | 16 | 1.350 | 32.9 | 3.23 | 59.72 |
| | 20 | 1.350 | 62.8 | 10.3 | 59.75 |
| | 24 | 1.350 | 46.29 | -13.83 | 59.71 |
| | 21 | 1.358 | 41.1 | 17.25 | 59.69 |
| | 23 | 1.358 | 37.12 | 12.69 | 59.66 |
| | 23 | 1.442 | 37.12 | 12.69 | 59.75 |
| | 21 | 1.458 | 41.1 | 17.25 | 59.80 |
| Total | | | 298.43 | 59.58 | |

Table 6.6 Generator Information at Steady Status after Disturbance

| Generator | P(MW) | | Q(Mvar) |
|---|---|---|---|
| G30 | 271.1 | 250 | 103.3 |
| G31 | 541.3 | 541.7 | 307.7 |
| G32 | 675.7 | 650 | 281.6 |
| G33 | 0 | 632 | 0 |
| G34 | 592.5 | 508 | 127.7 |
| G35 | 676.9 | 650 | 211.4 |
| G36 | 636 | 560 | 194 |
| G37 | 562.3 | 540 | -21.5 |
| G38 | 902.6 | 830 | 42.4 |
| G39 | 1001.8 | 1000 | 284.4 |
| Total | 5860.2 | 6161.7 | 1531 |

| | | | |
|---|---|---|---|
| Diff | 5860.2-(6161.7-632) = 330.5(Gov) | | |

This time, only 298.43MW load was shed, and the other generators output increase 330.5MW of active power and so the system frequency goes back at 60Hz. This two actions work together to make up the lost generation of G33, which is 632MW.

### 6.3.3 Analysis of the Bus33 Generator Trip Case

The Generator33 is in Area-III, so this time we will trip generator in Area-II. The traditional UFLS scheme is the same as Drop33 case, and the frequency response of no-UFLS and T_UFLS are shown below.

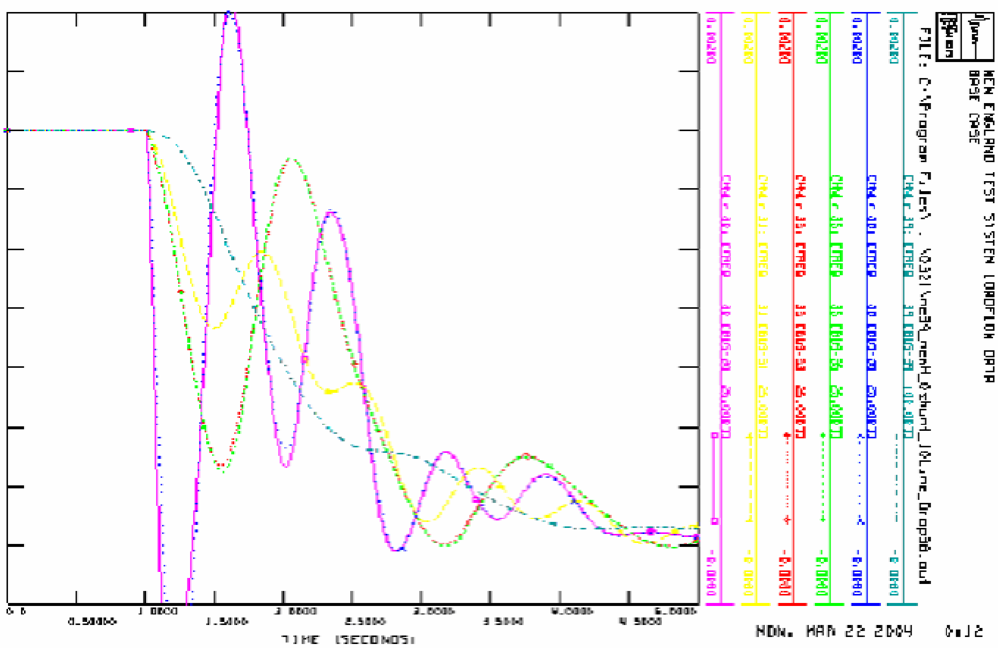



Figure 6.7 Frequency response of Gen 30, 31, 33, 35, 38, 39; Drop Gen38

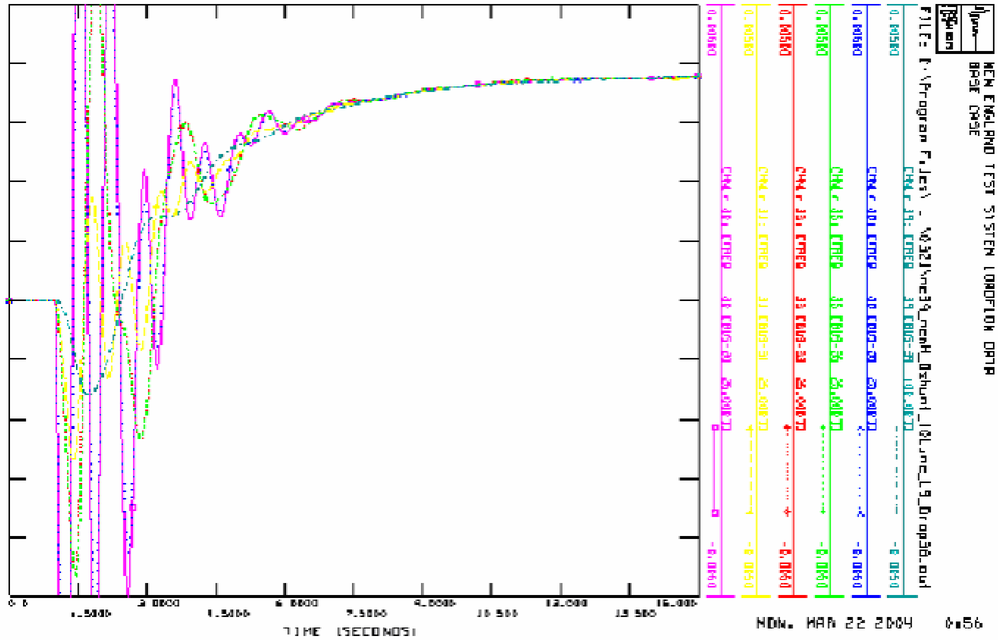


Figure 6.8 T_UFLS scheme, frequency response of Gen 30, 31, 33, 35, 38, 39

In traditional UFLS scheme, the total amount of shedding load is 807.23MW, and this cause over-shedding and the system frequency increase above 60Hz. This time the adaptive UFLS scheme has different setting with Drop33 case, the new setting of relays is:

3, 16, 18, 20, 21, 4, 7, 8, 12, 15, 23, 24, 31, 39
'LDSHBL', 1, 59.7, 0.1, 0.1, 59.6, 0.1, 0.15, 59.5, 0.1, 0.15, 0.1/
25, 26, 27, 28, 29
'LDSHBL', 1, 59.6, 0.1, 0.1, 59.5, 0.1, 0.20, 59.4, 0.1, 0.20, 0.1/

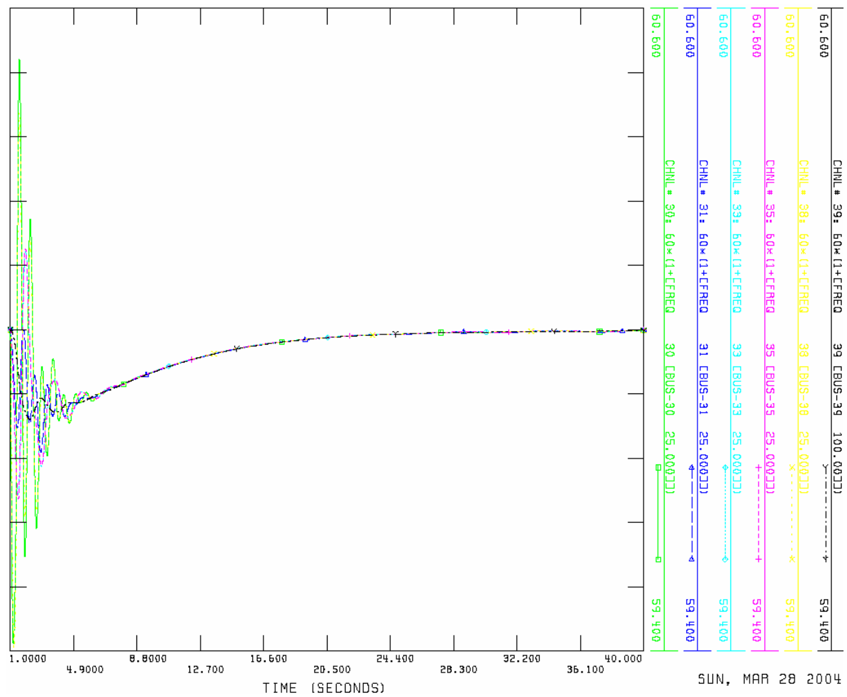



Figure 6.9 Adaptive UFLS scheme, frequency response of Gen 30, 31, 33, 35, 38, 39

Table 6.7 Shedding Load Information in Case of Drop38

| Trip Gen | Shed Location Bus | Shed Time Start at 1 s | Shed Load | | Shed Freq (Hz) |
|---|---|---|---|---|---|
| | | | P(MW) | Q(MVAR) | |
| 38 (830MW) | 3 | 1.3 | 32.2 | 0.24 | 59.53 |
| | 18 | 1.308 | 15.80 | 3.00 | 59.54 |
| | 25 | 1.325 | 22.40 | 4.72 | 59.53 |
| | 3 | 1.333 | 48.30 | 0.36 | 59.58 |
| | 26 | 1.333 | 13.90 | 1.70 | 59.55 |
| | 27 | 1.333 | 28.10 | 7.55 | 59.56 |
| | 28 | 1.333 | 20.60 | 2.76 | 59.52 |
| | 29 | 1.333 | 28.35 | 2.69 | 59.52 |
| | 18 | 1.342 | 23.70 | 4.50 | 59.60 |
| | 25 | 1. 358 | 44.80 | 9.44 | 59.63 |
| | 28 | 1.367 | 41.20 | 5.52 | 59.64 |
| | 29 | 1.367 | 56.70 | 5.38 | 59.64 |
| | 26 | 1.375 | 27.80 | 3.40 | 59.69 |
| | 27 | 1.383 | 56.20 | 15.10 | 59.73 |
| Total | | | 460.05 | 66.36 | |

Table 6.8 Generator Information at Steady Status after Disturbance

| Generator | P(MW) | | Q(Mvar) |
|---|---|---|---|
| G30 | 302.0 | 250 | 58.9 |
| G31 | 542.7 | 541.7 | 259.9 |
| G32 | 685.8 | 650 | 362.0 |
| G33 | 706.1 | 632 | 106 |

| | | | |
|---|---|---|---|
| G34 | 578.9 | 508 | 164.9 |
| G35 | 686.6 | 650 | 292.9 |
| G36 | 630.5 | 560 | 238.5 |
| G37 | 576.4 | 540 | -22.2 |
| G38 | 0 | 830 | 0 |
| G39 | 1005.3 | 1000 | 304.1 |
| Total | 5714.3 | 6161.7 | 1765 |
| Diff | 5714.3-(6161.7-830)=<br>5714.3-5331.7=382.6(Gov) | | |

This time, only 460.05MW load was shed, and the other generators output increase 382.6MW of active power and so the system frequency goes back at 60Hz. This two actions work together to make up the lost generation of G38, which is 830MW.

### 6.3.4 Summary of One Generator Trip Cases

Using the method of tripping G33, all other cases can be run in the same way and the summary of the shedding load is list in the following table:

Table 6.9 Comparison of two UFLS Schemes

| Generator | P (MW) | Q (Mvar) | T_UFLS(P) | | A_UFLS(P) | |
|---|---|---|---|---|---|---|
| G30 | 250 | 175.8 | N | N | 162.8 | 28.63 |
| G31 | 541.7 | 189.2 | 441.45 | 129.3 | 191.23 | 71.73 |
| G32 | 650 | 182.1 | 422.31 | 127.27 | 505.98 | 219 |
| G33 | 632 | 57 | 351.22 | 84.36 | 298.43 | 59.58 |
| G34 | 508 | 142.8 | 123.1 | 25.03 | 245.26 | 54.47 |
| G35 | 650 | 241.1 | 307.65 | 66.08 | 257.33 | 42.33 |
| G36 | 560 | 203 | 243.55 | 44.17 | 243.55 | 44.17 |
| G37 | 540 | 20.8 | 172.4 | 35.34 | 172.4 | 35.34 |
| G38 | 830 | 49.5 | 807.23 | 121.11 | 460.05 | 66.36 |
| Total | 6161.7 | | | | | |

In the table, the T_UFLS means when use the traditional UFLS scheme, the shedding load amount according to tripping each generator, and A_UFLS is the adaptive UFLS scheme.

From the table, the conclusion can be drawn that adaptive UFLS schemes can meet many kinds of disturbance, whether the deficient generation located in which area. The traditional UFLS schemes can deal with some cases such as Drop36 and Drop37, but it is not adaptive enough to deal with other cases. The shedding load amount is only a proportion of the disturbance amount because of the governor action. Moreover, the amount is about 50% of the tripped generation, so in this simulation system, when there is a disturbance occurs, only half part of disturbance amount need to be shed to make the system recover to a stable status.

### 6.3.5 Analysis of Two Generators Trip Case

In real power system, the under frequency load shedding relays' first step frequency is always set at 59.5, because when the frequency does not decline below 59.5, the disturbance will not be considered as a really severe accident. Only when the frequency decline reaches the level that could lead to tripping of steam turbine generating units by under frequency protective relays, in order to prevent extended operation of separated areas at lower than normal frequency, load shedding schemes are employed to reduce the connected load to a level that can be safely supplied by available generation.

In order to simulate this situation, more generators need to be tripped at starting point to create a case that the system frequency can decline below the setting level. This time, generator 33 and 35 will be tripped to create such a disturbance that will make the system frequency decline to the level that can trigger the action of UFLS relays in real system.

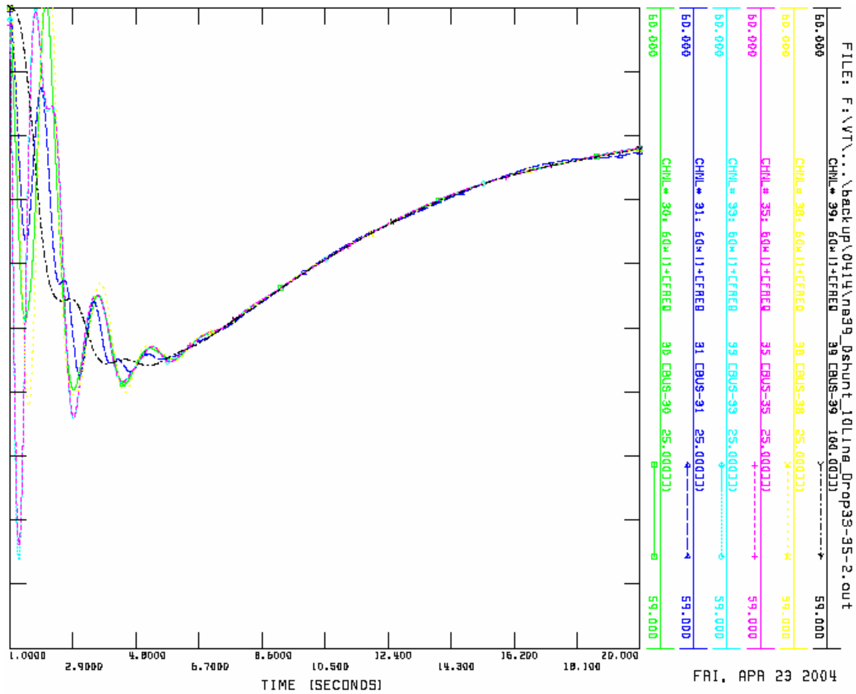



Figure 6.10 Drop33&35, without UFLS scheme, the frequency response

The simulation step is in this way:

Run the steady case for 1 second and trip G33&35 at the end of 1 second

Run for 0.2 second, and calculate the shedding amount with the equation from the information of frequency and the other parameters.

Table 6.10 Frequency information at each bus at 0.2 second

| Gen | Freq | Bus | Freq |
|---|---|---|---|
| 30 | 59.754 | 14 | 59.781 |
| 31 | 59.858 | 4 | 59.801 |
| 32 | 59.843 | 12 | 59.815 |
| 33(632) | 59.221 | 5 | 59.831 |
| 34(508) | 59.090 | 7 | 59.842 |
| 35(650) | 59.250 | 8 | 59.847 |
| 36(560) | 59.145 | 20 | 59.163 |
| 37 | 59.770 | 19 | 59.219 |
| 38 | 59.862 | 23 | 59.233 |
| 39 | 59.991 | 22 | 59.249 |
| | | 21 | 59.275 |
| | | 24 | 59.289 |
| | | 1 | 59.782 |

Employ the adaptive UFLS scheme, and set the relays' setting as following
3, 4, 7, 8, 12, 15, 18, 31, 39,
'LDSHBL',1, 59.5, 0.1, 0.15, 59.4, 0.1, 0.159, 59.2, 0.1, 0.165, 0.1/

16, 24, 'LDSHBL',1, 59.4, 0.1, 0.20, 59.2, 0.1, 0.159, 59.1, 0.1, 0.165, 0.1/
21, 23, 25, 26, 27, 28, 29
'LDSHBL',1, 59.4, 0.1, 0.15, 59.2, 0.1, 0.159, 59.1, 0.1, 0.165, 0.1/

And get the frequency response is shown in the following Figure

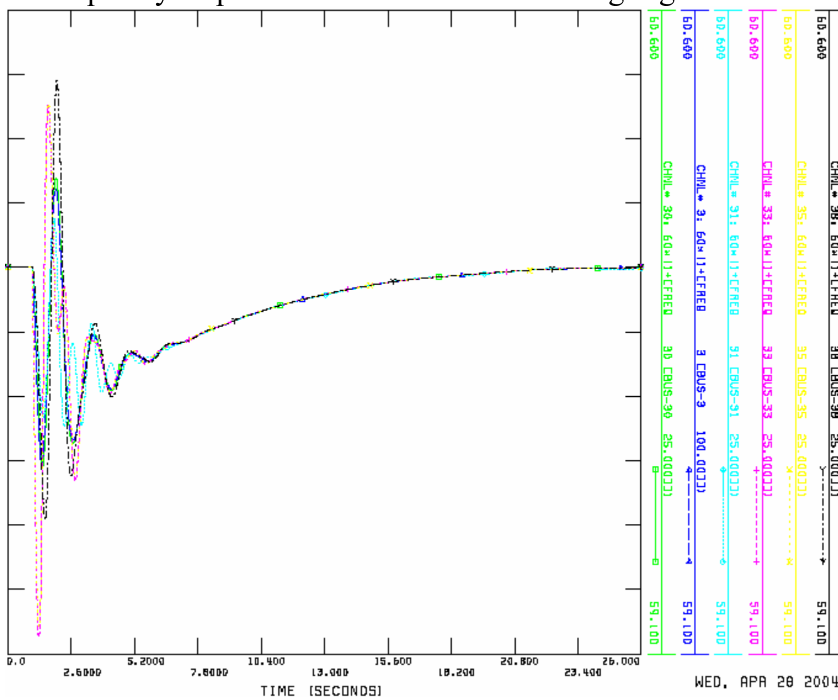



Figure 6.11 Adaptive UFLS scheme, frequency response of G30, 31, 33, 35, 38, 39

Table 6.11 Shedding Load Information in Case of Drop33&35

| Trip Gen | Shed Location Bus | Shed Time Start at 1 s | Shed Load | | Shed Freq (Hz) |
|---|---|---|---|---|---|
| | | | P(MW) | Q(MVAR) | |
| 33+35 (632+650) | 20 | 1.333 | 219.8 | 36.05 | 59.16 |
| | 23 | 1.350 | 37.12 | 12.69 | 59.22 |
| | 21 | 1.358 | 41.1 | 17.25 | 59.26 |
| | 16 | 1.367 | 65.8 | 6.46 | 59.30 |
| | 24 | 1.367 | 61.72 | -18.44 | 59.29 |
| | 20 | 1.392 | 99.85 | 16.38 | 59.4 |
| | 23 | 1.417 | 39.35 | 13.45 | 59.49 |
| Total | | | 564.74 | 83.84 | |

Table 6.12 Generator Information at Steady Status after Disturbance

| Generator | P(MW) | | Q(Mvar) |
|---|---|---|---|
| G30 | 298.8 | 250 | 58.9 |
| G31 | 543.4 | 541.7 | 259.9 |
| G32 | 708.0 | 650 | 362.0 |
| G33 | 0 | 632 | 106 |
| G34 | 715.1 | 508 | 164.9 |
| G35 | 0 | 650 | 292.9 |

| | | | |
|---|---|---|---|
| G36 | 747.5 | 560 | 238.5 |
| G37 | 589.5 | 540 | -22.2 |
| G38 | 999.5 | 830 | 0 |
| G39 | 997.4 | 1000 | 304.1 |
| Total | 5599.2 | 6161.7 | 1765 |
| Diff | 5599.2-(6161.7-632-650)=<br>5599.2-4879.7=719.5(Gov) | | |

564.74MWload was shed, and the other generators output increase 719.5MW of active power and so the system frequency goes back at 60Hz. This two actions work together to make up the lost generation of G33&35, which is (632+650) MW, $P_{shed} + P_{Gov} = 564.74 + 719.5 = 1284.24$ $P_{Lost} = 632 + 650 = 1282$ so we get : $P_{shed} + P_{Gov} \approx P_{Lost}$

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## 6.4 Scenario Analysis of UFLS in EUS System

Figure 6.12 shows the coverage area of the system model with some identified 345 kV and higher voltage lines/buses in EUS.

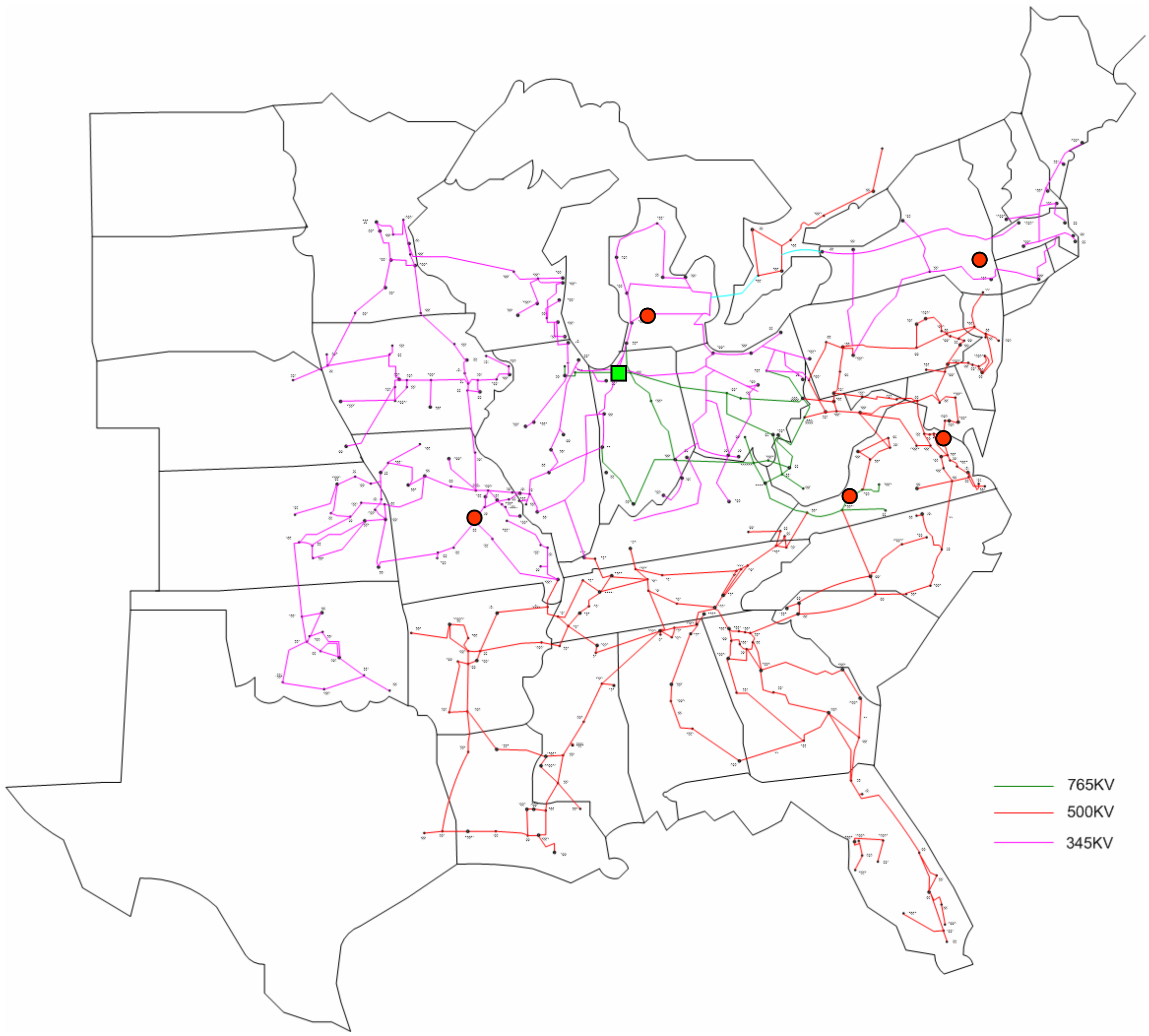


Figure 6.12 EUS transmission system of 345 kV and higher voltage levels

The system is a comprehensive and detailed model, which contains the voltage level from 765 kV down to the distribution levels. There are more FDR units in the EUS system than that in WECC system, while the capacity of the EUS system is much larger than WECC system. In this means, when the same amount of generation is tripped in the two systems, the response of WECC is more distinct than that in the EUS system. The FNET system is sensitive enough to catch the small frequency drop. With frequency information from FDR units in the EUS system, if an unexpected event occurs, the location of this event can be estimated by triangulation analysis and the amount of generation change can be estimated. The FNET system started running from this summer, during this period there are four significant generator tripped events in EUS as we know. These four events are listed in the following table with date and detailed time.

Simulation Steps

- Trip the generator at bus 21630 at 0.5 sec
- Apply UFLS model at bus 21630, 28881, 28696, 28855
- Observe frequency at bus 21630, 78980(NY), 96041(UMR), 14053(ARI), 22567(VT), 28197(Calvin)

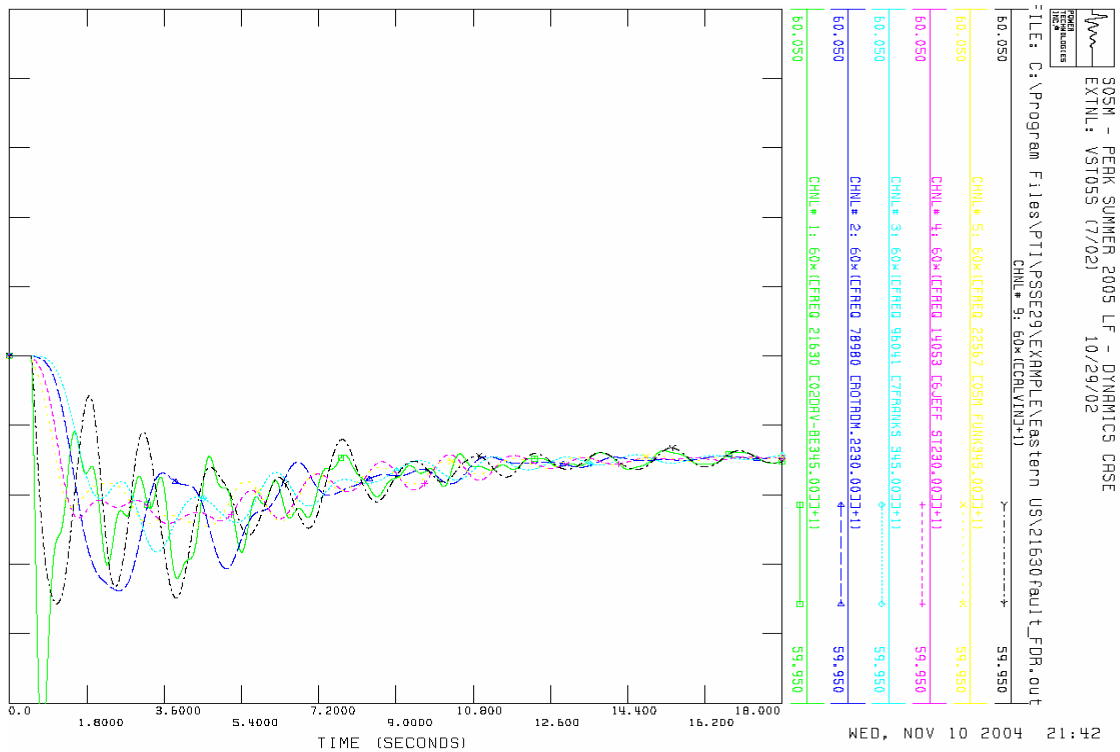


Figure 6.13 the frequency response without load shedding scheme

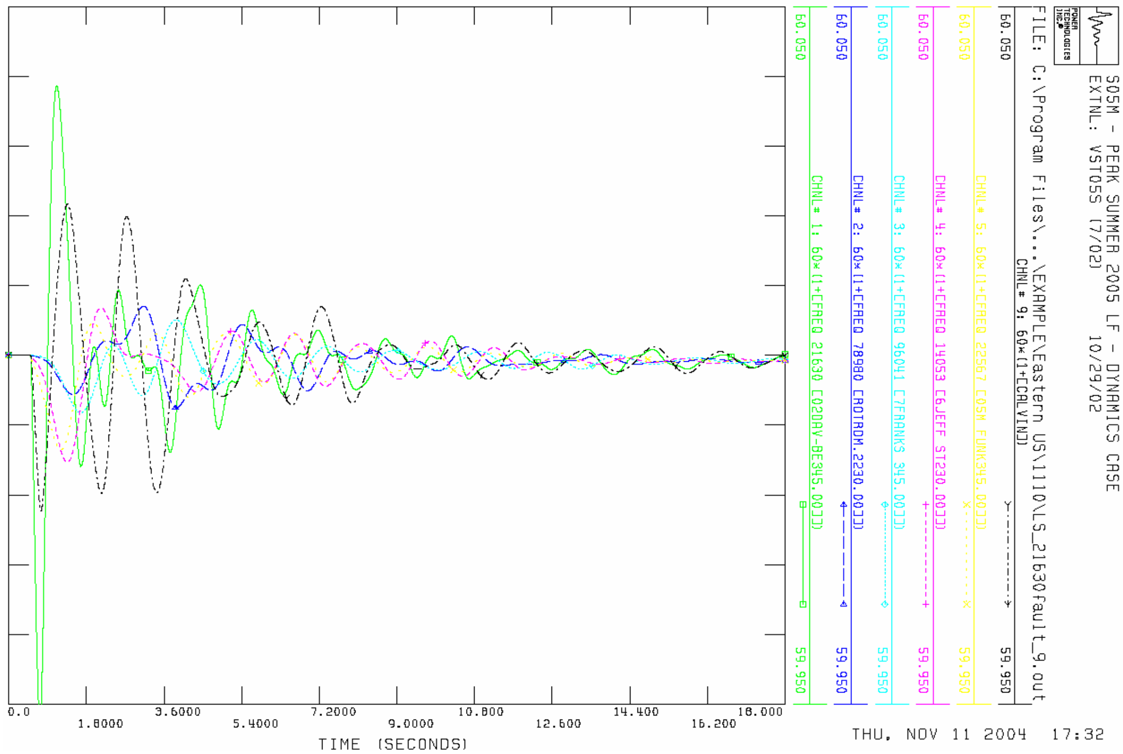

Figure 6.14  Frequency response with adaptive UFLS scheme

- Total Shed Load: 2587.52MW
  - Bus21630, 244.58MW+71.4MVAR
  - Bus28881, 707.14MW+306.18MVAR
  - Bus28696, 769.95MW+210.53MVAR
  - Bus28855, 865.85MW+211.43MVAR
- Tripped Generation
  - Bus21630, 2550.9MW+40.8MVAR

## 6.5 Summary

A new adaptive under frequency load shedding scheme based on wide area measurement is presented in this report. Through the computer simulations of the 3-area multi-machine power system, the sensitivity of the power system frequency response to the disturbance location is investigated in detail. In order to design an adaptive scheme, the problem of disturbance location, distribution of shedding load, and shedding time need be included. The simulation results show that this scheme is quite efficient in these cases.

# Chapter 7 Conclusion and Future Research

## 7.1 Conclusions

The massive power outages of 2003 summer and some large scale events happened in recent years disclose that power systems are far from what they suppose to be, and reveal the vulnerability of the over stressed power grids. Post-event analysis and reports show that an important reason of these events is a lack in awareness of the power system status information and so real-time monitoring of this critical infrastructure becomes an urgent agenda in order to ensure a healthy economy.

FNET stands for frequency monitoring network. The system implements WAMS in a way that the frequencies of the whole US & Canada power grid can be collected and managed in a central server. Continuous synchronized wide area frequency information will provide system operators with near real-time system status. This dissertation briefly describes how to implement the FNET system and uses collected data to demonstrate how to use FNET to monitor and analyze the power system disturbance. With their integrated GPS receivers, FDR units can simultaneously measure the local system frequency in different dispersed locations. FNET provides a common time stamp, which helps reconstruct major events. The FNET system started operation in November of 2003, and FDR units have been installed in 15 locations as of July 2005. The FNET system has made observations of the country's entire power network possible for the first time.

The FDR unit built at Virginia Tech uses the same frequency calculation phasor algorithm with PMU, and some modifications are added to ensure the FDR can work with 110 V signal. Comparison result between FDR and PMU is addressed, which illustrate that FDR can get the required accuracy and has the advantage of low cost, fast deployment and so on. The comparison shows that the FDR can monitor the frequency of power system and has the same accuracy compare to PMU

FNET provides valuable data for studies of inter-area oscillations, disturbance analysis, scenario reconstruction, and model verification. With the implementation of the first phase of FNET system, the raw field-measured frequency is investigated in this chapter. General system operating frequency is examined and the characteristics of frequency deviation of the EUS, WECC and ERCOT are given. The propagation of frequency in distribution system is analyzed and the result shows the 110V outlet frequency can represent the system frequency. Some statistical analysis of frequency is given and long-term frequency pattern is investigated. Standard deviation reveals a measure of the dispersion or variation in a distribution. The daily analysis of frequency shows the operation pattern of the EUS. In addition to observing transient states of the system, we can also use the FNET data to observe system's frequency oscillation and one example case is provided.

The frequency disturbance analysis is addressed, and the frequency trigger is designed to detect the significant frequency fluctuation in each interconnection. The location of the disturbance can be estimated by the pattern of frequency drop delay with the triangulation technique and TDOA method, the algorithm is designed to analyze the known cases, and the result shows the estimation is relatively good enough. The further estimation is introduced to get location that is more detailed. Using the empirical equations, changed generation in the disturbance can be estimated with good accuracy. Some example cases are provided to show how to use FNET to monitor and analyze power system disturbance.

With FNET information, especially when combined with existing EMS data, better load shedding schemes can be developed. An adaptive UFLS is designed and tested with the simulation in New England 39-bus system and EUS system with PSS/E. This can be achieved in stages. First, new knowledge from FNET historical measurement records can help better understand overall system frequency patterns and improve load-frequency modeling accuracy, which will enhance simulation results that are used to design control strategies and load shedding schemes. Later, with better communication capability, using real-time FNET data combined with EMS information, adaptive load-shedding schemes can be used to shed load based on actual load distribution and power flow constraints.

In the future, researchers hope to use the data from the FNET system to forecast incipient system breakups and recommend remedial actions. The continuous synchronized information from the FNET system will provide system operators with close to real-time system status for better grid management. With future high-speed communication, the real-time wide-area frequency information can be used in many areas to perform control and protection functions. The FNET system provides power system researchers, operators, customers, and policy makers an Internet accessible, cost-effective, cross-platform frequency information monitoring network.

## 7.2 Contributions

This dissertation work provides the following contributions:

1. Implement the first phase Frequency Monitoring Network
2. Design and develop the IMS server, including server program, database, communication protocol, web service
3. Modify and revise the code of frequency disturbance recorder
4. Test the FDR and compare with PMU
5. Setup and maintain the FNET server
6. Serve as the computer manage and administrator of Power IT Lab
7. Design and develop the analysis method to process frequency data
8. Design and develop the frequency disturbance analysis tools, including disturbance detection, location, and generation estimation
9. Discuss in detail several known frequency disturbance cases
10. Design and test the adaptive UFLS scheme

## 7.3 Future work

There are some areas where future research is necessary to continue this research work.

1. Further investigation in the recorded frequency data, this will involve in the tools and algorithm design to analyze the increasing raw data. The field-measured data can provide much first hand system information with proper analysis tools.
2. Data integration with EMS and PMU, frequency data from FNET can be a supplemental information to the regulation department, utility, and researchers
3. routine data handling and processing, design and develop some program to generate statistic frequency report periodically, this kind of report can be use to analyze the frequency control pattern
4. disturbance catalog and detection, because current trigger can only detect the generation tripping event, while there are some other kind of disturbance can be detected with frequency data, such as transmission line trip, load rejection and so on
5. improve the accuracy of disturbance location, more algorithm need be investigated and the geographical information
6. graphical user interface and web access to the raw frequency, more display method to facilitate the visualization of frequency data,
7. further application of FNET information in power system:
   - Verify system models and parameters used in simulations
   - Perform post-disturbance scenario reconstruction and track the sequence of events leading to an emergency
   - Understand the fundamental characteristics and mathematics of failure of complex systems
   - Provide near real-time system status for analyzing the underlying causes of cascading events and system blackouts
   - FNET frequency as inputs for FACTS/ESS control in inter-area low frequency oscillation damping
   - ACE accuracy improvement with FNET data
   - Wide area PSS control and coordination using FNET as inputs
   - Distributed Generation (DG) control and coordination using regional FNET measurements

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# Appendix A FNET Server Program Manual

This section provides an overview of the software structure of FNET. The purpose of this document is to assist programmer in the further enhancement and development of this software. This section will describe the software structure and the operations of all the classes of object build for the system.

## A.1 Main Program Structure

The FNET software consists of three main tiers:

- The Man Machine Interface (MMI)
- The communication using windows sockets.
- Database manipulation.

The application is built on dialog box template in Microsoft Visual C++ 6.0, and the application (release version) can run on the platform series of Windows Operation System. The Application class CFNETReceiverApp will setup a dialog box template and run three classes of object. The CMySocket handles the socket communication while the CFNETReceiverDlg provide the MMI.

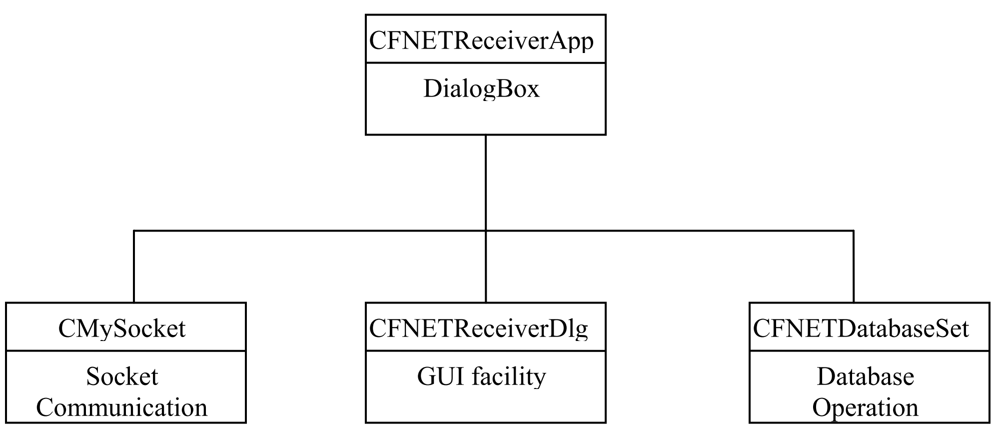



Figure A.1 Software Structure of Server Program

## A.2 User Interface Description

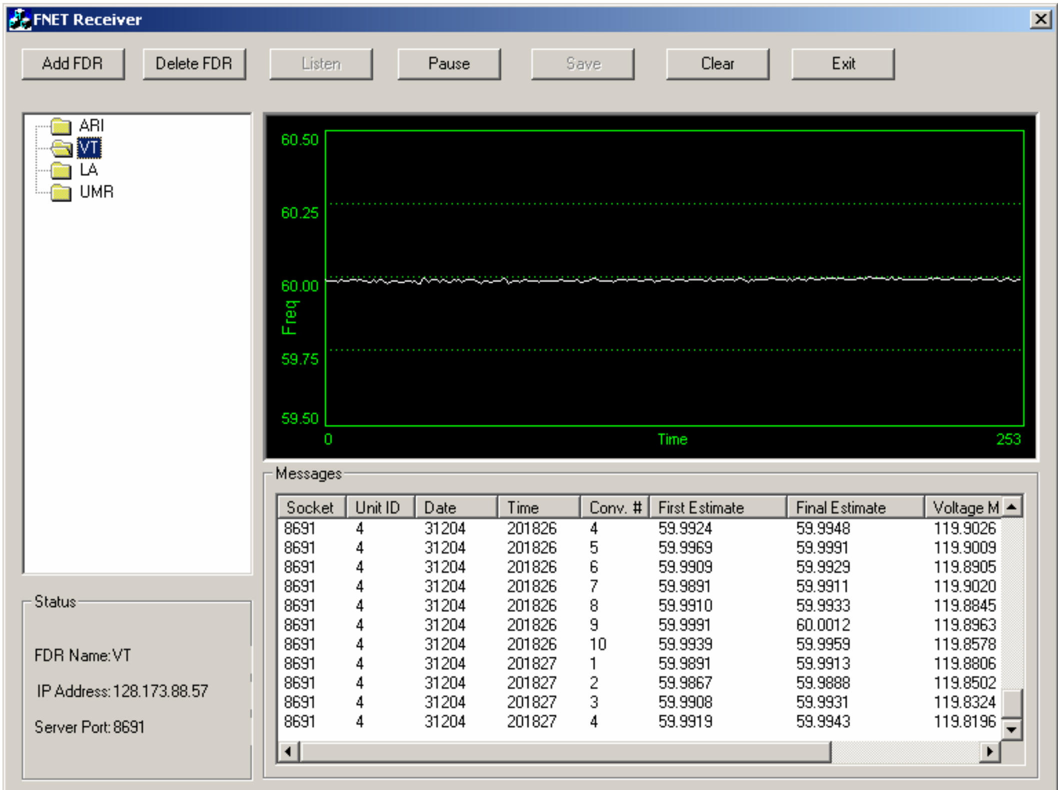


Figure A.2 Multi-unit Server Program Interface

There are four parts in the user interface screen. They are

1. TreeView shows FNET clients (FDR) from different sites, here we use the site location as the name of FDR.

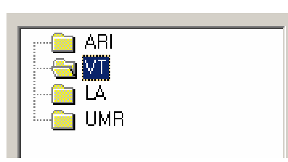


Figure A.3 TreeView of the GUI

2. Group Box shows the selected FDR's status: the location, IP address of the FDR unit and its relative port number in server side

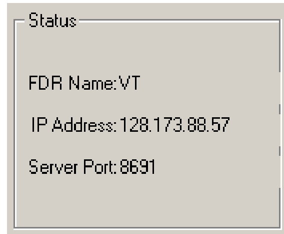



Figure A.4 Status window of GUI

3. Graph class – COScopeCtrl displays the selected FDR's frequency graph. The resolution of the graph can be set at the time of adding the relative FDR.

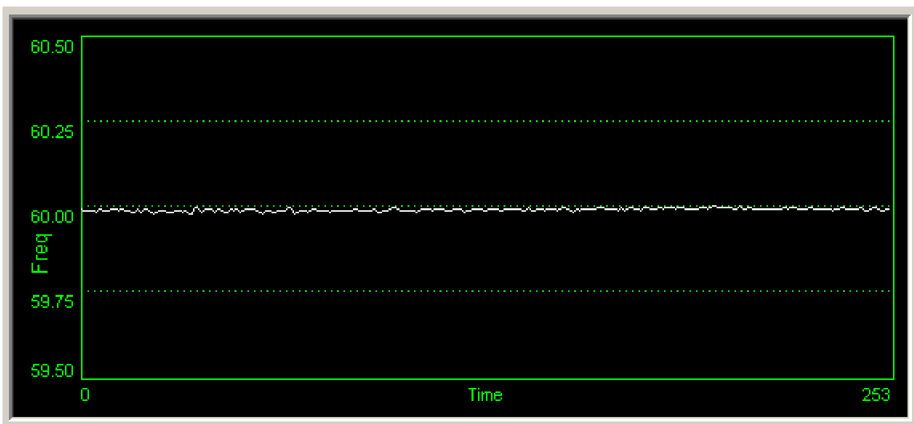
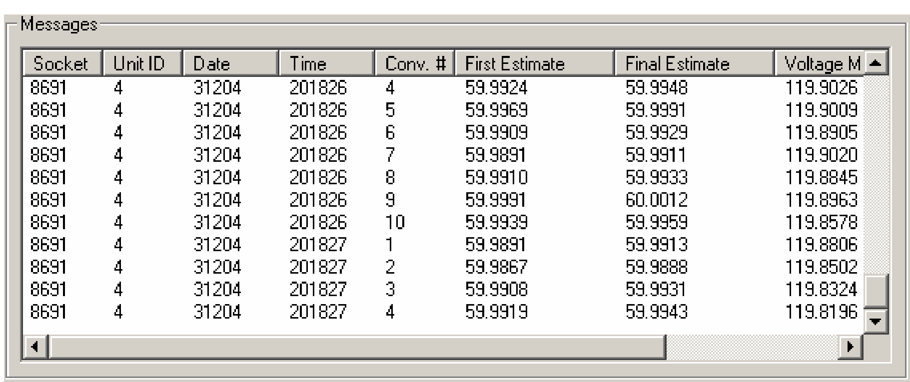



Figure A.5 Plot Window of GUI

4. List Box shows all the messages in the server from the selected FDR, there are eight items in the coming message: UnitID, Date, Time, ConvNum, First Freq, Final Freq, Voltage Magnitude, Voltage angle. These messages will be stored in background when displayed in the screen.


Messages

| Socket | Unit ID | Date | Time | Conv. # | First Estimate | Final Estimate | Voltage M |
|---|---|---|---|---|---|---|---|
| 8691 | 4 | 31204 | 201826 | 4 | 59.9924 | 59.9948 | 119.9026 |
| 8691 | 4 | 31204 | 201826 | 5 | 59.9969 | 59.9991 | 119.9009 |
| 8691 | 4 | 31204 | 201826 | 6 | 59.9909 | 59.9929 | 119.8905 |
| 8691 | 4 | 31204 | 201826 | 7 | 59.9891 | 59.9911 | 119.9020 |
| 8691 | 4 | 31204 | 201826 | 8 | 59.9910 | 59.9933 | 119.8845 |
| 8691 | 4 | 31204 | 201826 | 9 | 59.9991 | 60.0012 | 119.8963 |
| 8691 | 4 | 31204 | 201826 | 10 | 59.9939 | 59.9959 | 119.8578 |
| 8691 | 4 | 31204 | 201827 | 1 | 59.9891 | 59.9913 | 119.8806 |
| 8691 | 4 | 31204 | 201827 | 2 | 59.9867 | 59.9888 | 119.8502 |
| 8691 | 4 | 31204 | 201827 | 3 | 59.9908 | 59.9931 | 119.8324 |
| 8691 | 4 | 31204 | 201827 | 4 | 59.9919 | 59.9943 | 119.8196 |

Figure A.6 Message Window of GUI

# A.3 User Interface Operation

The server program starts with no FDR, and so some operation need to be done for the server to receive the information and data from FDR clients.

## A.3.1 Add new FDR to the Server

In order to add new FDR in the server, you need first click the "AddFDR" button on the top of interface, and the following dialog will popup:

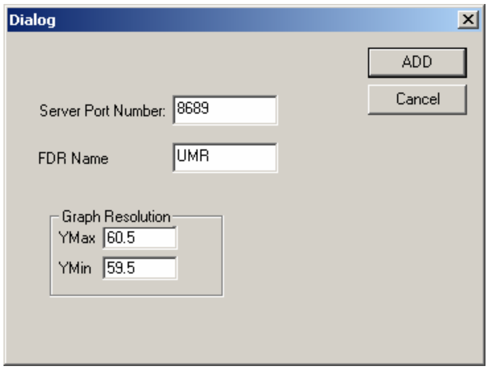



Figure A.7 Add New Unit Dialog

Input the information the dialog needed.

- Server Port Number: the port need to be opened for this FDR, before input the number, first check the port number which has been using;
- FDR Name: the name of FDR used in server and database, usually use the location as FDR name;
- Graph Resolution (Ymax & YMin): these two parameters are the maximum and minimum frequency limit and are graph resolution when this FDR is selected to be displayed in the screen.

After input all needed information, click ADD to return to main interface. If there is a client transmits the data to the opened port, the graph will start to plot the frequency, the message box will flash all the data in the screen and the status box will shows the information of this added FDR.

### A.3.2 Observe another FDR in the Server

If you need to observe another FDR, just double click the FDR's name in the left side tree view. After your select, the graph will clear the last FDR frequency plot and start a new plot for the selected one, the message box will also clear the data of last FDR and start to flash the data of this one, so will the message box.

### A.3.3 Delete a FDR in the Server

If one FDR stops to communication or it is removed, this FDR can be deleted in the server. First, select the FDR in the left side TreeView, and then click the "Delete FDR" button on the top of server. There will be a confirmation window for this operation, if this FDR really need to be deleted from this server, just click Delete in this confirmation window.

This operation just closes the pointed port and stops receiving any information from this FDR, and it will not affect in database. The data and information of this FDR will not be deleted from database.

### A.3.4 Stop and Exit the Server

This operation will close all the opening ports and stop all processes receiving information. Click the "Exit" button on the top of server is ok.

## A.4 Communication through the Socket

The CFNETReceiverDlg object will create a series of listening socket objects from the class CMySocket. The CMySocket is the class object used for the actual communication. The CFNETReceiverDlg will uses the string stream structure receive and transmit message or command through the socket. In order to ensure efficiency, attempt to connect any CMySocket will run as a separate thread.

In the server side, the server need to be start first and provide service based on request:

- Open the relative ports and tell local host that the server can receive client request on these ports,
- Wait for the client request to these ports,
- Notify this listening socket that it can accept pending connection requests by calling Accept. Then the socket calls Receive to deal with this connection request,
- Back to second step,
- Close

In the client side,

- Open communication channel and connect to the specific port of the server
- Send request for communication and wait for the accept message,
- Close channel and stop communication

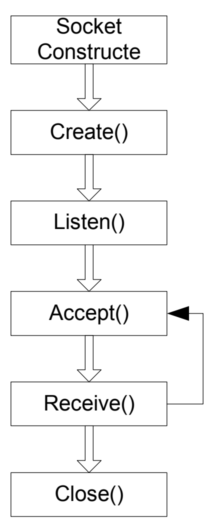



Figure A.8 Flow Chart of Communication Structure

## A.5 Database Design

The FNET database is built with Microsoft Access 2000. Two databases are required and maintained in the software. The FNET.mdb contains record of the FDR clients' information and data. There are two type of Table in this database; FDRInfo contains the FDR information, while FDRRawdata contains the data while the LoginList.mdb contains the login name and password. CLSSet map and open the LSBase.mdb while CSecuritySet maps to the LoginList.mdb.

CDIFBase and CIEDBase are used as temporary array to contain data on DIF and IED separately from LSBase.mdb.

*Database Details Definition*

| **Table Name** | FDRInfo |
|---|---|
| **Fundamental Responsibilities** | Store the information of FDR clients |
| **Field Name** | **Data Type** |
| FDR_Client_IP | Text |
| FDR_Location | Text |
| FDR_Client_portNum | Number/Integer |
| CreatTime(EST) | Date/Time |

| **Table Name** | FDRRawData# |
|---|---|
| **Fundamental Responsibilities** | Store the incoming data from the FDR clients |
| **Field Name** | **Data Type** |
| ConvNum | Number/Integer |
| Sample_Date&Time(UTC) | Date/Time |
| FirstFreq | Number/Single |
| FinalFreq | Number/Single |
| UnitID | Number/Byte |
| voltageMag | Number/Single |
| voltageAng | Number/Single |
| DateCreated(EST) | Date/Time |

# A.6 Class Details Definition

This section will briefly describe the operation of all the classes used in FNET software system.

## A.6.1 CFNETReceiverDlg Class

| **Class Name** | CFNETReceiverDlg |
|---|---|
| **Parent Class** | CDialog |
| **Fundamental Responsibilities** | The base class from which a Windows application object is derived. An application object provides member functions for initializing application and for running the application. |
| **Operations** | **Description** |
| CFNETReceiverDlg () | Class Constructor |
| AddDatabaseRawData () | Put the coming data into background ACCESS database |
| AddListItem () | Put the coming data for screen message display |
| AddMySQL() | Put the coming data into MySQL database for web |
| AutomaticBackup() | Save the ACCESS data file, and open a new file daily |
| CloseMySQL() | Close the connection with MySQL database |
| DatabaseConnectionClose () | Close the connection with ACCESS database |
| DatabaseConnectionOpen () | Open the connection with ACCESS database |
| DoDataExchange () | Exchange the data |
| FillListCtrlHeaders() | Fill the message ListCtrl headers |
| InitGraph () | Initialize the screen graph information |
| OnAddPMU () | Reaction to popup window to add a new FDR client |
| OnClear () | Clear the screen information(graph and message window) |
| OnDblclkTree() | Reaction when double click tree view |
| OnDelPMU() | Reaction to delete a new FDR client |

| | |
|---|---|
| OnInitDialog() | Initialize the dialog |
| OnPaint() | |
| OnQueryDragIcon() | |
| OnSysCommand() | |
| OpenMySQL() | Open the connection with MySQL database |
| ProcessClose() | Close the process of message management |
| ProcessMessage() | Get the information from socket function and send these to database and screen |
| SendData(ListItem &lItem) | Send the data to a second server **TESTING** |
| StatusDisplay() | Display the status of selected FDR |

### A.6.2 CFNETReceiverApp Class

| | |
|---|---|
| **Class Name** | CFNETReceiverApp |
| **Parent Class** | CWinApp |
| **Fundamental Responsibilities** | The base class from which a Windows application object is derived. An application object provides member functions for initializing application and for running the application. |
| **Operations** | **Description** |
| CFNETReceiverApp () | Class Constructor |
| InitInstance () | Initialize the application |

### A.6.3 CMySocket Class

| | |
|---|---|
| **Class Name** | CMySocket |
| **Parent Class** | CAsyncSocket |
| **Fundamental Responsibilities** | Manage the client socket communication, data transmission. |
| **Operations** | **Description** |
| CMySocket () | Class Constructor |

| | |
|---|---|
| ~CMySocket () | Initialize the application |
| OnAccept () | Reaction when connection request from client arrives |
| OnClose () | Reaction when the socket need to be closed |
| OnReceive () | Reaction when the socket starts to receive information and data from client |
| SetParent () | Set the parent object of this class |
| ValidateMessage () | Determine whether the incoming data is complete or not |

### A.6.4 COScopeCtrl Class

| | |
|---|---|
| **Class Name** | COScopeCtrl |
| **Parent Class** | CWnd |
| **Fundamental Responsibilities** | The base class from which a display window is derived. The window is used for plotting the frequency of the selected FDR |
| **Operations** | **Description** |
| COScopeCtrl () | Class Constructor |
| ~COScopeCtrl () | Class Destructor |
| AppendPoint () | Append a new point for plotting |
| Create () | A new object of this class is created |
| DrawPoint() | Draw the point of window |
| InvalidateCtrl() | |
| OnPaint() | |
| OnSize () | |
| Reset() | |
| SetBackgroundColor() | Set the color of window background |
| SetGridColor() | Set the color of window grid |
| SetPlotColor() | Set the color of plot curve |
| SetRange() | Set the range of plot curve |

| | |
|---|---|
| SetShiftPixels() | Set the shift pixels of plot curve |
| SetXUnits() | Set the unit of x axis |
| SetYUnits() | Set the unit of Y axis |

### A.6.5 CPMUDlg Class

| | |
|---|---|
| **Class Name** | CPMUDlg |
| **Parent Class** | Cdialog |
| **Fundamental Responsibilities** | The base class from which a Windows application object is derived. An application object provides member functions for initializing application and for running the application. |
| **Operations** | **Description** |
| CPMUDlg () | Class Constructor |
| DoDataExchange () | Initialize the application |
| OnOK() | Reaction when the ok button is clicked |

### A.6.6 CFNETRecord Class

| | |
|---|---|
| **Class Name** | CFNETRecord |
| **Parent Class** | CRecordset |
| **Fundamental Responsibilities** | MySQL database class used for adding frequency data to MySQL database. |
| **Operations** | **Description** |
| CFNETRecord () | Class Constructor |

### A.6.7 ListItem Struct

| | |
|---|---|
| **Struct Name** | ListItem |
| **Fundamental Responsibilities** | The base class from which a Windows application object is derived. An application object provides |

| | |
|---|---|
| | member functions for initializing application and for running the application. |
| **Data Member** | **Description** |
| string socketNum | The relative port number of socket of the object |
| string time | Sampled Time of the data |
| string time_Date | Sampled date of the data |
| string convNum | The number of the data in 1 second |
| string firstFreq | The measured temporary frequency |
| string finalFreq | The measured final frequency |
| string UnitID | The specific unit ID of FDR |
| string voltageMag | The measured voltage magnitude |
| string voltageAng | The measured voltage angle |
| CString PMUIPAddress | The IP Address of FDR |
| CString PMUName | The name of FDR |
| int m_isocketPortNum | The number this socket process |
| int ItemNum | The item number of this socket process |
| double YMax, YMin | The graph resolution of frequency |

# Appendix B PHP Code of FNET Web Server

```
<?// If the username and password are incorrect/missing, prompt for them
$user = "fnet";
$pass = "virginiatech";

if (!isset($HTTP_POST_VARS['username'])){
        $HTTP_POST_VARS['username'] = '';
        $HTTP_POST_VARS['password'] = '';
}

if (!($HTTP_POST_VARS['username'] == $user && ($HTTP_POST_VARS['password']
== $pass || $HTTP_POST_VARS['password']=="test"||
$HTTP_POST_VARS['password']=="testaccess"))){
        echo<<<END
<html><body>
<form method="post" action="index.php" name="login"><font face="arial">
<table border="0">
<tr><td colspan="2" align="center"><a href="http://www.vt.edu/" title="Virginia Tech
Homepage"><img src="vtlogo.gif" border="0"></a></td></tr>
<!--<tr><td colspan="2" align="center" aa464b><a href="http://www.ece.vt.edu/"
title="The Bradley Department of Electrical and Computer Engineering "><img
src="eceinside.gif" border="0"></a><br><br></td></tr></td><td><font size="3"
color="#aa464b">-->
<tr></tr><tr></tr><tr></tr>
<tr><td align="center">Username:<input name="username" type="text" value=""
size="13"><br></td></tr>
<tr><td align="center">Password:<input name="password" type="password" value=""
size="13"><br></td></tr>
<tr><td align="center">      <input
type="submit" value="Login"></td></tr>
<tr><td colspan="2" align="center"><a href="http://www.ece.vt.edu/" title="Dept. of
ECE"><img src="bradley.gif" border="0"></a></td></tr>
<tr><td align="center"><font size="3" color="#990000">The Bradley Department of
Electrical and Computer Engineering</font></td></tr>
<tr><td align="center"><font size="3" color="#990000">Any comments please contact
<a href="mailto:acss@vt.edu">zzhong@vt.edu</a> </font></td></tr>
</table>
</font></form>
</body></html>
END;
        exit;
}

//echo "Computer Time:".gmdate('D, d M Y H:i:s \G\M\T', time())."<br>";
```

```
//connect to MySQL database
$conn = mysql_connect("localhost","root","") or die ("Could not connect to localhost");
$db = mysql_select_db("fnetserver", $conn);

// The query includes < '30000000000000' because older dates were formatted with
month first
$result = mysql_query("select * from serverinfo where time < '30000000000000' order
by time desc limit 0, 10", $conn);

// Colors used for freq deviation
$color0 = "#ffffff";
$color1 = "#ff0000";
$color2 = "#ffaf00";
$color3 = "#ffff00";
$color4 = "#00ff00";
$color5 = "#00ffff";
$color6 = "#00afff";
$color7 = "#000fff";
?>

<html>
<head>
<!--<META HTTP-EQUIV="Refresh" CONTENT="5; URL=index.php"> -->
<script language="JavaScript">
<!-- // JS refresh: http://grizzlyweb.com/webmaster/javascripts/refresh.asp
var sURL = unescape(window.location.pathname);

function doLoad()
{   // the timeout value should be the same as in the "refresh" meta-tag
    setTimeout( "refresh()", 5*1000 );
}

function refresh()
{   //  This version of the refresh function will cause a new
    //  entry in the visitor's history.  It is provided for
    //  those browsers that only support JavaScript 1.0.
    //
    //window.location.href = sURL;
    document.forms[0].submit();
}

//-->
</script>
<meta http-equiv="Content-Type" content="text/html; charset=windows-1252">
<title>FNET Server Streamer</title>
```

```
</head>
<body onLoad="doLoad()">

<font face="Arial" size="4"><b>Welcome to FNET Server of Virginia Tech
<br></font>
<font face="Geneva" size="3" color="990000"><I>at The Bradley Department of
Electrical and Computer Engineering</I></b></font><br><br>
Color Vs Frequency
<br>

<table border="1">
<tr>
<td bgcolor="<?=$color7?>"><59.90</td>
<td bgcolor="<?=$color6?>">59.90~59.95</td>
<td bgcolor="<?=$color5?>">59.95~59.99</td>
<td bgcolor="<?=$color4?>">59.99~60.01</td>
<td bgcolor="<?=$color3?>">60.01~60.05</td>
<td bgcolor="<?=$color2?>">60.05~60.10</td>
<td bgcolor="<?=$color1?>">>60.10</td>
<td>NO DATA</td>
</tr>
</table><br>
Time Zone:UTC<br><br>

<?
echo '<table border="1" cellspacing="2">';
// Get the number of rows and columns so that when more columns are added, the page
automatically adjusts.
$num_fields = mysql_num_fields($result);
$num_rows = 10; // 10 rows = 1 minute (set in query)// mysql_num_rows($result);

// Load values to a 2-D array so they can be printed properly
$i=0;
while ($row = mysql_fetch_row($result)){
        for($j=0; $j<$num_fields; $j++){
        $FreqArray[$j][$i] = $row[$j];
        }
        $i++;
}

// Print a row for each fnet box
/*for($i=0;$i<$num_fields-1;$i++){
        echo "<tr>\n  <td>";
        echo mysql_field_name($result, $i);
        echo "</td>";
        for($j=$num_rows-1; $j>=0; $j--){
```

```
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)       echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}*/
/*
//Unit at NY, UMR, ARI, VT
for($i=0;$i<4;$i++){
          echo "<tr>\n  <td>";
          echo mysql_field_name($result, $i);
          echo "</td>";
          for($j=$num_rows-1; $j>=0; $j--){
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)       echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
```

```
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}
//Unit at MISS
for($i=6;$i<7;$i++){
          echo "<tr>\n  <td>";
          echo mysql_field_name($result, $i);
          echo "</td>";
          for($j=$num_rows-1; $j>=0; $j--){
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)       echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}

//Unit at UFL
for($i=8;$i<9;$i++){
          echo "<tr>\n  <td>";
          echo mysql_field_name($result, $i);
          echo "</td>";
          for($j=$num_rows-1; $j>=0; $j--){
```

```
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)        echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}

//Unit at Calvin
for($i=10;$i<11;$i++){
          echo "<tr>\n  <td>";
          echo "Calvin";//mysql_field_name($result, $i);
          echo "</td>";
          for($j=$num_rows-1; $j>=0; $j--){
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)        echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
```

```
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}
//Unit at ABB,Raleigh
for($i=5;$i<6;$i++){
          echo "<tr>\n  <td>";
          echo "ABB";//mysql_field_name($result, $i);
          echo "</td>";
          for($j=$num_rows-1; $j>=0; $j--){
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)       echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}

//Unit at Tulane
for($i=16;$i<17;$i++){
          echo "<tr>\n  <td>";
          echo "Tulane";//mysql_field_name($result, $i);
          echo "</td>";
          for($j=$num_rows-1; $j>=0; $j--){
```

```
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)       echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}

//Unit at Seattle
for($i=4;$i<5;$i++){
          echo "<tr>\n  <td>";
          echo "Seattle";//mysql_field_name($result, $i);
          echo "</td>";
          for($j=$num_rows-1; $j>=0; $j--){
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)       echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
```

```
			else if($freq>59.80)	echo "<td bgcolor=\"$color7\" 
valign=\"top\">".$freq."</td>";
			else if($freq>58.00)	echo "<td bgcolor=\"$color7\" 
valign=\"top\">".$freq."</td>";
			else if($freq<=58.0)	echo "<td align=\"middle\"><font color=\"#ff0000\" 
size=\"2\">NO DATA</font></td>";
		}
		echo "\n</tr>";
}

//Unit at CA
for($i=7;$i<8;$i++){
		echo "<tr>\n  <td>";
		echo "EPRI";//echo mysql_field_name($result, $i);
		echo "</td>";
		for($j=$num_rows-1; $j>=0; $j--){
			$freq = $FreqArray[$i][$j];
			   if($freq >60.2)		echo "<td bgcolor=\"$color1\" 
valign=\"top\">".$freq."</td>";
			else if($freq>60.10)	echo "<td bgcolor=\"$color1\" 
valign=\"top\">".$freq."</td>";
			else if($freq>60.05)	echo "<td bgcolor=\"$color2\" 
valign=\"top\">".$freq."</td>";
			else if($freq>60.01)	echo "<td bgcolor=\"$color3\" 
valign=\"top\">".$freq."</td>";
			else if($freq>59.99)	echo "<td bgcolor=\"$color4\" 
valign=\"top\">".$freq."</td>";
			else if($freq>59.95)	echo "<td bgcolor=\"$color5\" 
valign=\"top\">".$freq."</td>";
			else if($freq>59.90)	echo "<td bgcolor=\"$color6\" 
valign=\"top\">".$freq."</td>";
			else if($freq>59.80)	echo "<td bgcolor=\"$color7\" 
valign=\"top\">".$freq."</td>";
			else if($freq>58.00)	echo "<td bgcolor=\"$color7\" 
valign=\"top\">".$freq."</td>";
			else if($freq<=58.0)	echo "<td align=\"middle\"><font color=\"#ff0000\" 
size=\"2\">NO DATA</font></td>";
		}
		echo "\n</tr>";
}

//Unit at ASU
for($i=13;$i<14;$i++){
		echo "<tr>\n  <td>";
		echo "ASU";//mysql_field_name($result, $i);
		echo "</td>";
```

```
	for($j=$num_rows-1; $j>=0; $j--){
		$freq = $FreqArray[$i][$j];
		   if($freq >60.2)	echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
		else if($freq>60.10)	echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
		else if($freq>60.05)	echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
		else if($freq>60.01)	echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
		else if($freq>59.99)	echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
		else if($freq>59.95)	echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
		else if($freq>59.90)	echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
		else if($freq>59.80)	echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
		else if($freq>58.00)	echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
		else if($freq<=58.0)	echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
	}
	echo "\n</tr>";
}

//Unit at LA
for($i=15;$i<16;$i++){
	echo "<tr>\n  <td>";
	echo "LA";//mysql_field_name($result, $i);
	echo "</td>";
	for($j=$num_rows-1; $j>=0; $j--){
		$freq = $FreqArray[$i][$j];
		   if($freq >60.2)	echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
		else if($freq>60.10)	echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
		else if($freq>60.05)	echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
		else if($freq>60.01)	echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
		else if($freq>59.99)	echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
		else if($freq>59.95)	echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
```

```
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}

//Unit at Houston
for($i=11;$i<12;$i++){
          echo "<tr>\n  <td>";
          echo "Houston";//mysql_field_name($result, $i);
          echo "</td>";
          for($j=$num_rows-1; $j>=0; $j--){
                    $freq = $FreqArray[$i][$j];
                        if($freq >60.2)       echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.10)    echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.05)    echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                    else if($freq>60.01)    echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.99)    echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.95)    echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.90)    echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
                    else if($freq>59.80)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq>58.00)    echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                    else if($freq<=58.0)    echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
          }
          echo "\n</tr>";
}
*/

//Unit at Houston
for($i=9;$i<10;$i++){
```

```
        echo "<tr>\n  <td>";
        echo "Houston";//mysql_field_name($result, $i);
        echo "</td>";
        for($j=$num_rows-1; $j>=0; $j--){
                $freq = $FreqArray[$i][$j];
                    if($freq >60.2)      echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                else if($freq>60.10)   echo "<td bgcolor=\"$color1\"
valign=\"top\">".$freq."</td>";
                else if($freq>60.05)   echo "<td bgcolor=\"$color2\"
valign=\"top\">".$freq."</td>";
                else if($freq>60.01)   echo "<td bgcolor=\"$color3\"
valign=\"top\">".$freq."</td>";
                else if($freq>59.99)   echo "<td bgcolor=\"$color4\"
valign=\"top\">".$freq."</td>";
                else if($freq>59.95)   echo "<td bgcolor=\"$color5\"
valign=\"top\">".$freq."</td>";
                else if($freq>59.90)   echo "<td bgcolor=\"$color6\"
valign=\"top\">".$freq."</td>";
                else if($freq>59.80)   echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                else if($freq>58.00)   echo "<td bgcolor=\"$color7\"
valign=\"top\">".$freq."</td>";
                else if($freq<=58.0)   echo "<td align=\"middle\"><font color=\"#ff0000\"
size=\"2\">NO DATA</font></td>";
        }
        echo "\n</tr>";
}

echo "<tr>";
echo "<td>UTC Time</td>"; // mysql_field_name($result, $num_fields-1);
// Now print out the times
for($j=$num_rows-1; $j>=0; $j--){
        $temp=$FreqArray[$num_fields-1][$j];
        echo "<td align=\"center\" valign=\"top\">";
        echo substr($temp,4,2).'/'.substr($temp,6,2).'/'.substr($temp,0,4).'<br>'
        .substr($temp,8,2).':'.substr($temp,10,2).':'.substr($temp,12,2)."</td>";
}
echo "</tr>\n</table>";

mysql_close($conn);
?>

<form method=post action="index.php" name="refresh">
<input name="username" type="hidden"
value="<?=$HTTP_POST_VARS['username']?>">
```

```
<input name="password" type="hidden"
value="<?=$HTTP_POST_VARS['password']?>">
</form>

<form method=post action="mapindex.php" name="mapversion">
<input name="username" type="hidden"
value="<?=$HTTP_POST_VARS['username']?>">
<input name="password" type="hidden"
value="<?=$HTTP_POST_VARS['password']?>">
<input name="mv_submit" value="Map Version" type="submit">

</form>

<p><font size="5" color="#ff0000">The FNET Server is being continuously modified
and you may see temporary hold and data out on this page.</font><br><br>
<font size="2" color="#ff0000">The data displayed here is a 5-second average result,
there are 10 points every second.<br><br>
You must have a JavaScript compatible browser for this page to refresh
automatically<br><br>
If you have any comments, please send an email to zzhong@vt.edu</font></p>

</body>
</html>
```

# Appendix C Daily Frequency Oscillation Spectrum Matlab Code and Result Plot

```
function data_analysis_oscillation(year, month, day)
%clear all
%year = 2005; month = 4; day = 21;
event_start_time = [year month day 0 0 10];
event_end_time = [year month day 23 59 58];

fig1on=0; %10 point averaging plot
fig2on=0; %raw data plot
fig3on=0; %wavelet denoise data plot
fig4on=1; %oscillation analysis

findfreqflag=0;
datapath = ['I:\SplitDate\'];

year_c = num2str(year); month_c = num2str(month); day_c = num2str(day);
if length(month_c)==1,
   month_c = ['0',month_c]; end
if length(day_c)==1
   day_c = ['0',day_c]; end

datafile = ['fdr-',num2str(year_c),'-',month_c,'-',day_c,'-EST.mat'];

%------------------------------------------------------------------------
units = [1 2 3 4 6 7 9 11 17];
unitsname = ['NY ';'UMR';'ARI';'VT ';'ABB';'MIS';'UFL';'CAL';'TLN'];
%MIS: Missiisspii, CAL: Calvin College, TLN: Tulane University ;'TVA'
%------------------------------------------------------------------------
%units = 11;
%unitsname = ['CAL'];
%units = 12;
%unitsname = ['TX'];
%------------------------------------------------------------------------
%units = [5 8 14 16];
%unitsname = ['SEA';'CA ';'ASU';'LA '];
%STL: Seattle, CA: EPRI, ASU: Arizona State University,

% find the frequency time at the spotted region
findstart_time = [2005 3 25 11 01 00];
findend_time = [2004 11 23 11 01 20];
findfreq = 59.98;
```

```
if fig1on==1
   fig1 = figure;
   ax1 = [];
   hold on
end
if fig2on==1
   fig2 = figure;
   ax2=[];
   hold on
end
if fig3on==1
   fig3 = figure;
   ax3 = [];
   hold on
end
if fig4on==1
   fig4 = figure;
   ax4 = [];
   hold on
end
cmat = colormap('jet');
legendtxtk=1;
for k=1:length(units)
   warning off
   eval(['load ',datapath,datafile,' FDR',num2str(units(k)),';']);
   warning on
   if exist(['FDR',num2str(units(k))],'var')
      eval(['FDR',num2str(units(k)),'_event_start_indx = min(find(datenum(FDR',...
         num2str(units(k)),'.date)>datenum(event_start_time)));']);
      eval(['FDR',num2str(units(k)),'_event_end_indx = max(find(datenum(FDR',...
         num2str(units(k)),'.date)<datenum(event_end_time)));']);
      eval(['tmpindx1 = FDR',num2str(units(k)),'_event_start_indx;']);
      eval(['tmpindx2 = FDR',num2str(units(k)),'_event_end_indx;']);
      if tmpindx1 >0 & tmpindx2>0 & tmpindx2>tmpindx1
         eval(['FDRdata = FDR',num2str(units(k)),';']);
         FDRdataraw.freq = FDRdata.freq(tmpindx1:tmpindx2);
         FDRdataraw.date = FDRdata.date(tmpindx1:tmpindx2,:);
         FDRdata.freq = FDRdata.freq(tmpindx1:tmpindx2);
         FDRdata.date = FDRdata.date(tmpindx1:tmpindx2,:);
         windowSize = 10;
         FDRdata.freq = filter(ones(1,windowSize)/windowSize,1,FDRdata.freq);    %
running average
         % 2 round average
         FDRdata.avefreq = filter(ones(1,windowSize)/windowSize,1,FDRdata.freq);

         %Calculate the oscillation of the frequency
```

```
        FDRdata.oscillation = (FDRdataraw.freq(windowSize/2:end-windowSize/2) -
FDRdata.freq(windowSize:end));
        Y = fft(FDRdata.oscillation,51200);
        Pyy = Y.* conj(Y) / 51200;
        f = 10*(0:25600)/51200;

        title('Oscillation content of the frequency')
        xlabel('frequency (Hz)')

        if length(FDRdataraw.freq)>0
           if fig1on==1
              figure(fig1);
              ax1(legendtxtk) =
plot(datenum(FDRdata.date(windowSize:end,:)),FDRdata.freq(windowSize:end));
              %set(ax1,'Color',cmat(1+round((k-1)*64/length(units)),:))
           end
           if fig2on==1
              figure(fig2);
              ax2 = plot(datenum(FDRdataraw.date),FDRdataraw.freq);
              set(ax2,'Color',cmat(1+round((k-1)*64/length(units)),:))
           end

           if fig3on==1
              % denoise the data
              freqdata = wden(FDRdataraw.freq,'heursure','h','one',3,'db4');
              figure(fig3);
              ax3(legendtxtk) = plot(datenum(FDRdataraw.date),freqdata);
              %set(ax3,'Color',cmat(1+round((k-1)*64/length(units)),:))
           end

           if fig4on==1
              figure(fig4);
              ax4(legendtxtk) = plot(f,Pyy(1:25601));
            end

           legendtxt{legendtxtk} = ['FDR',num2str(units(k)),' - ',unitsname(k,:)];
           legendtxtk = legendtxtk+1;
        end
        %title(['Unit ',num2str(units(k))]);
        %-------------------------------------------------
        % find the target frequency time
        if findfreqflag==1
           FDRdata_findstart_indx =
min(find(datenum(FDRdata.date)>datenum(findstart_time)));
           FDRdata_findend_indx =
max(find(datenum(FDRdata.date)<datenum(findend_time)));
```

```
            FDRdata.date =
FDRdata.date(FDRdata_findstart_indx:FDRdata_findend_indx,:);
            FDRdata.freq =
FDRdata.freq(FDRdata_findstart_indx:FDRdata_findend_indx);
            [y,i]=min(abs(FDRdata.freq-findfreq));
            if FDRdata.freq(i) < findfreq
               slope = (datenum(FDRdata.date(i-1,:))-
datenum(FDRdata.date(i,:)))/(FDRdata.freq(i-1) - FDRdata.freq(i));
               findfreqtime = slope*(findfreq-FDRdata.freq(i))+datenum(FDRdata.date(i,:));
               disp(['The neaby 2 points times are ',num2str(FDRdata.date(i-
1,4)),':',num2str(FDRdata.date(i-1,5)),':',num2str(FDRdata.date(i-1,6)),...
                  ' and
',num2str(FDRdata.date(i,4)),':',num2str(FDRdata.date(i,5)),':',num2str(FDRdata.date(i,6)
)])
            elseif FDRdata.freq(i) > findfreq
               slope = (datenum(FDRdata.date(i,:))-
datenum(FDRdata.date(i+1,:)))/(FDRdata.freq(i) - FDRdata.freq(i+1));
               findfreqtime = slope*(findfreq-
FDRdata.freq(i+1))+datenum(FDRdata.date(i+1,:));
               disp(['The neaby 2 points times are
',num2str(FDRdata.date(i,4)),':',num2str(FDRdata.date(i,5)),':',num2str(FDRdata.date(i,6)
),...
                  ' and
',num2str(FDRdata.date(i+1,4)),':',num2str(FDRdata.date(i+1,5)),':',num2str(FDRdata.dat
e(i+1,6))])
            else
               findfreqtime = datenum(FDRdata.date(i));
            end

            disp(['FDR',num2str(units(k)),' ',num2str(findfreq),'Hz time is
',datestr(findfreqtime,13)]);
         end
      end
   end
   %-----------------------------------------------------------

end
linecolor = ['b','g','r','c','m','k','y'];
cmat1 = [1,0,0;    0,0.5,0;    0,0,1;    0.75,0,0.75;    0.75,0.75,0;    0.6,0.2,0; 0.25,0.25,0.25;
   1,0.69,0.39];

cmat = colormap('jet');
if fig1on==1
   figure(fig1);
   if length(ax1)<=8
      for k=1:length(ax1)
```

```
            set(ax1(k),'Color',cmat1(k,:));
        end
    else
        for k=1:length(ax1)
            set(ax1(k),'Color',cmat(1+round((k-1)*16/length(ax1)),:))
        end
    end
    legend(legendtxt);
    title([num2str(year),'/',num2str(month),'/',num2str(day),' ',num2str(windowSize),'-point
average']);
    ylabel('Frequency (Hz)');
    xlabel('Time (EST)');
    dynamic_date_axis
end
if fig2on==1
    figure(fig2);
    if length(ax2)<=8
        for k=1:length(ax3)
            set(ax2(k),'Color',cmat1(k,:));
        end
    else
        for k=1:length(ax3)
            set(ax2(k),'Color',cmat(1+round((k-1)*64/length(ax2)),:))
        end
    end
    legend(legendtxt);
    title([num2str(year),'/',num2str(month),'/',num2str(day),' ','raw data']);
    ylabel('Frequency (Hz)');
    xlabel('Time (EST)');
    dynamic_date_axis
end
if fig3on==1
    figure(fig3);
    if length(ax3)<=8
        for k=1:length(ax3)
            set(ax3(k),'Color',cmat1(k,:));
        end
    else
        for k=1:length(ax3)
            set(ax3(k),'Color',cmat(1+round((k-1)*64/length(ax3)),:))
        end
    end
    legend(legendtxt);
    title([num2str(year),'/',num2str(month),'/',num2str(day),' -wavelet denoise']);
    ylabel('Frequency (Hz)');
    xlabel('Time (EST)');
```

```
    dynamic_date_axis
end

if fig4on==1
    figure(fig4);
    if length(ax4)<=8
        for k=1:length(ax4)
            set(ax4(k),'Color',cmat1(k,:));
        end
    else
        for k=1:length(ax4)
            set(ax4(k),'Color',cmat(1+round((k-1)*64/length(ax4)),:))
        end
    end
    legend(legendtxt);
    title([num2str(year),'/',num2str(month),'/',num2str(day),' -Oscillation Analysis']);
    ylabel('Power Spectrum');
    xlabel('Frequency (Hz)');
end
```

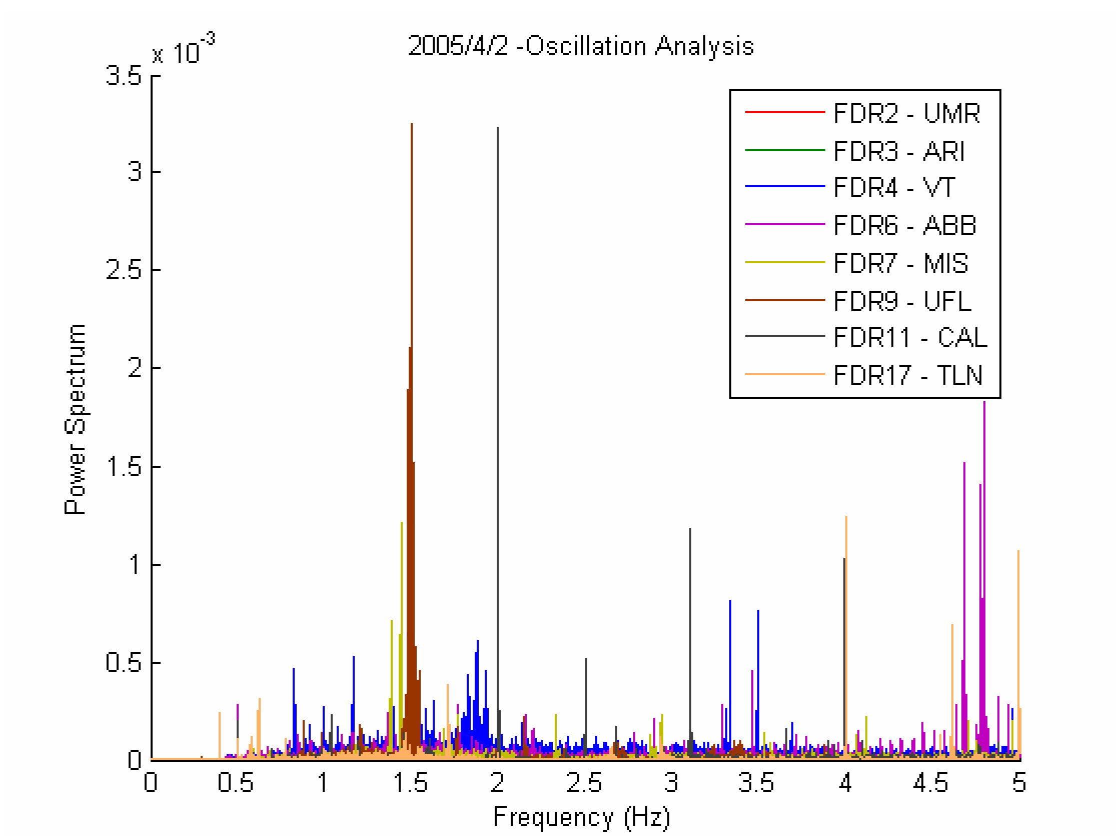



Figure C.1 Spectrum Analysis of Frequency Oscillation on Apr. 2, 2005

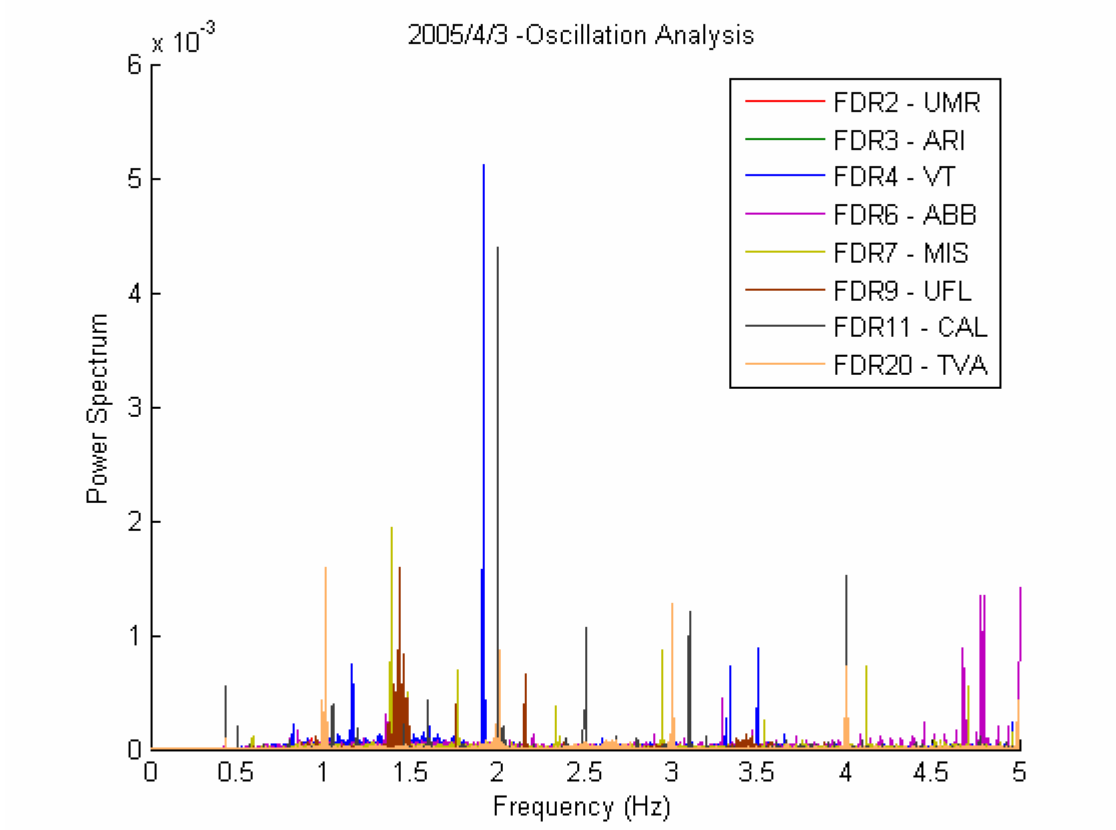



Figure C.2 Spectrum Analysis of Frequency Oscillation on Apr. 3, 2005

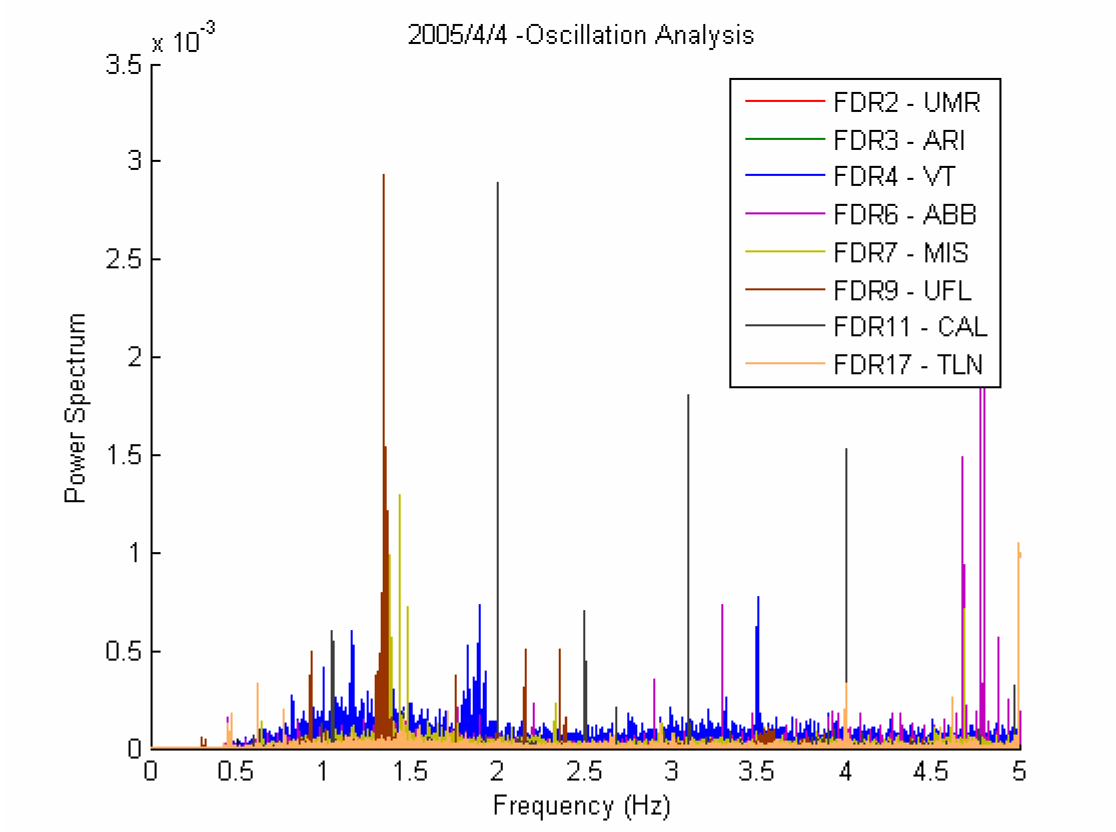



Figure C.3 Spectrum Analysis of Frequency Oscillation on Apr. 4, 2005

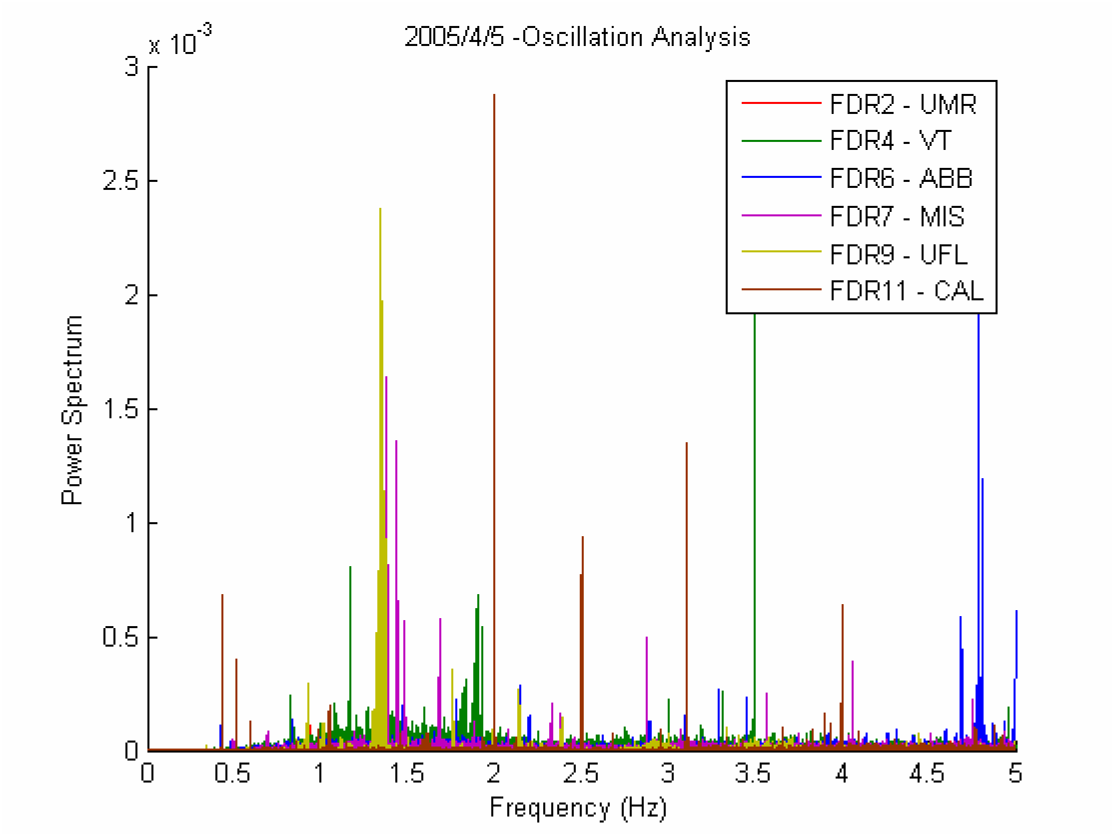



Figure C.4 Spectrum Analysis of Frequency Oscillation on Apr. 5, 2005

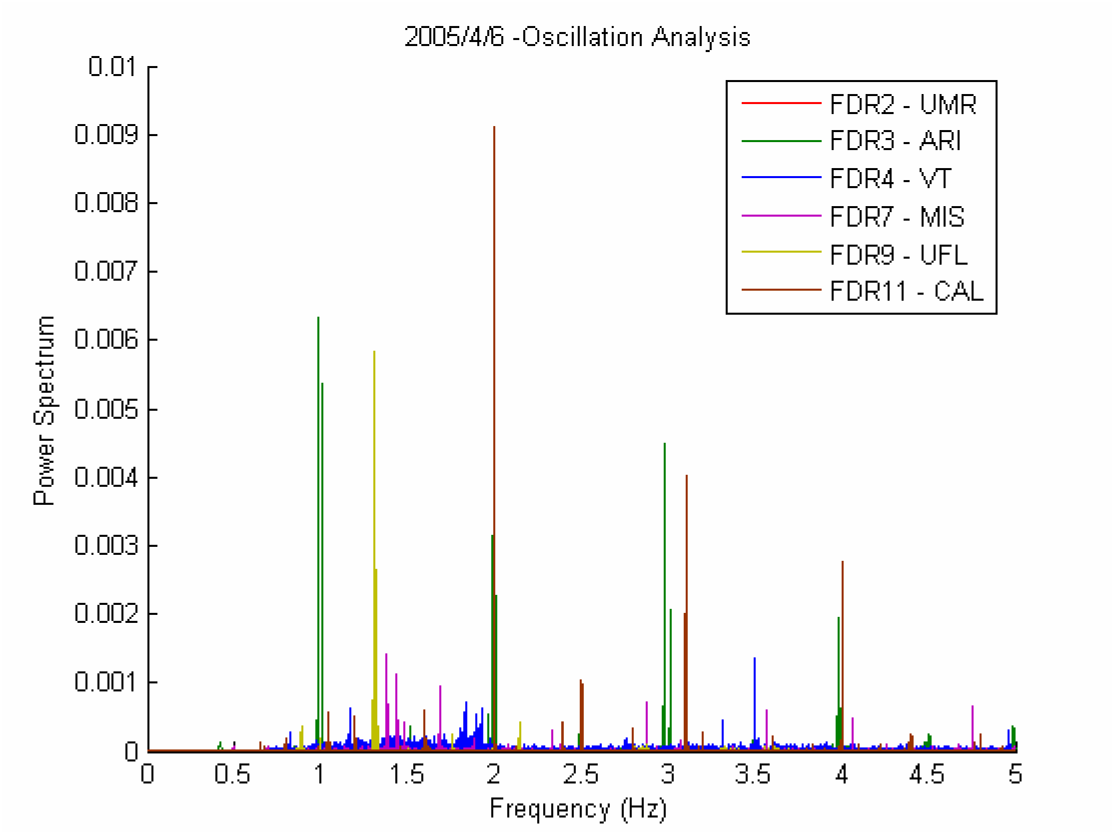



Figure C.5 Spectrum Analysis of Frequency Oscillation on Apr. 6, 2005

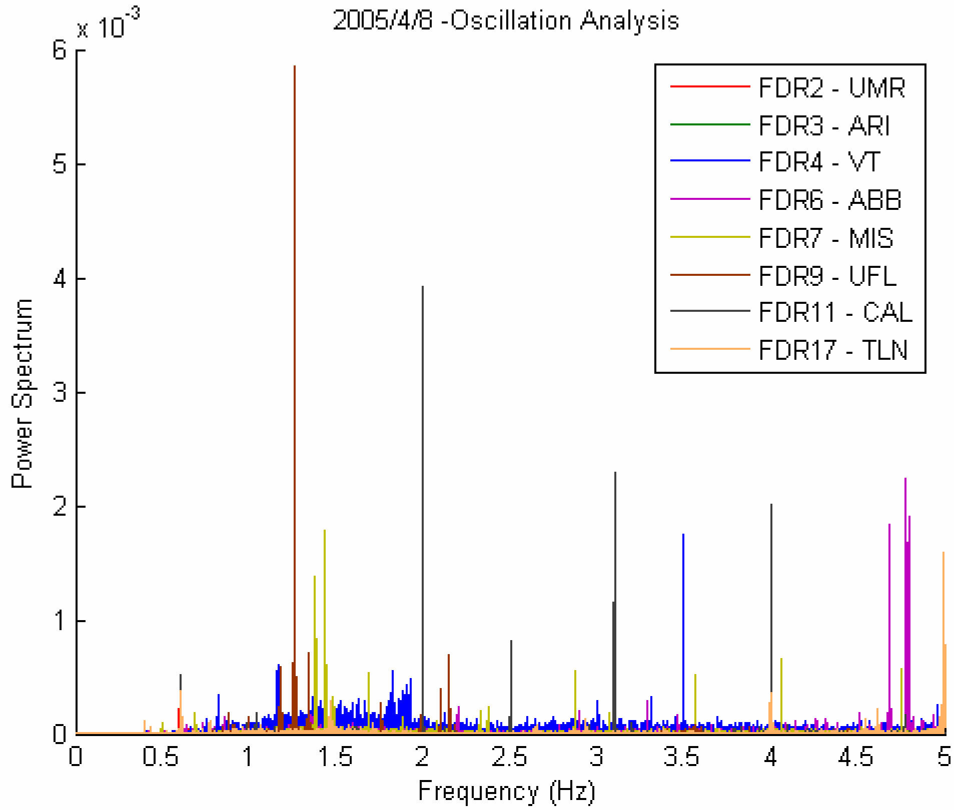



Figure C.6 Spectrum Analysis of Frequency Oscillation on Apr. 8, 2005

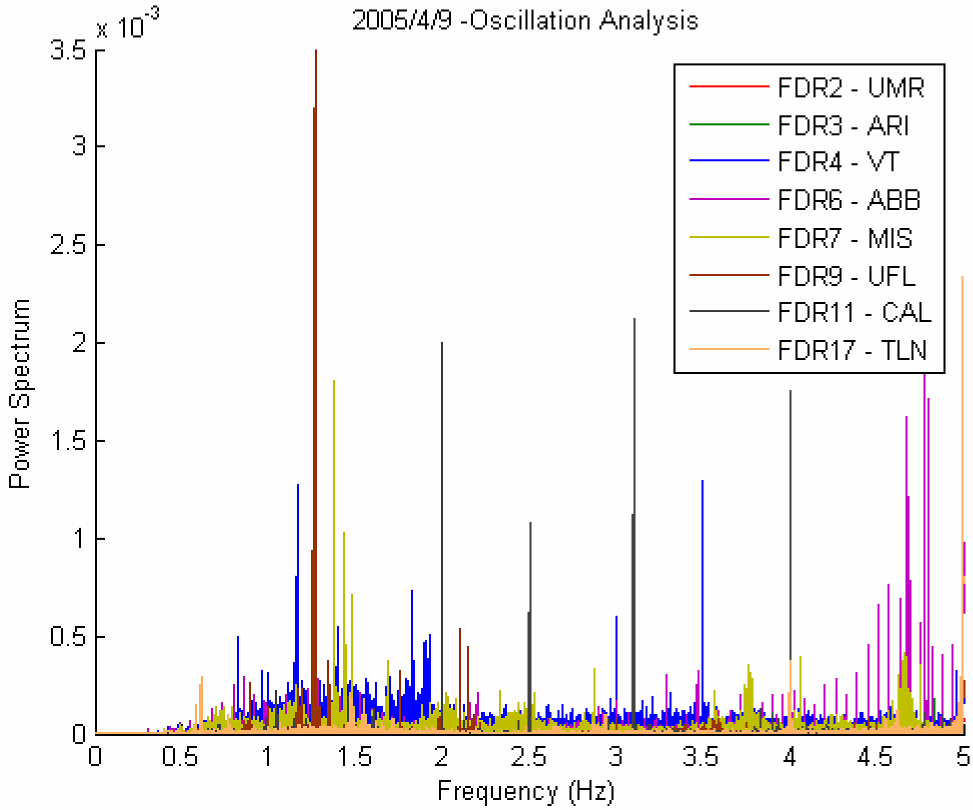



Figure C.7 Spectrum Analysis of Frequency Oscillation on Apr. 9, 2005

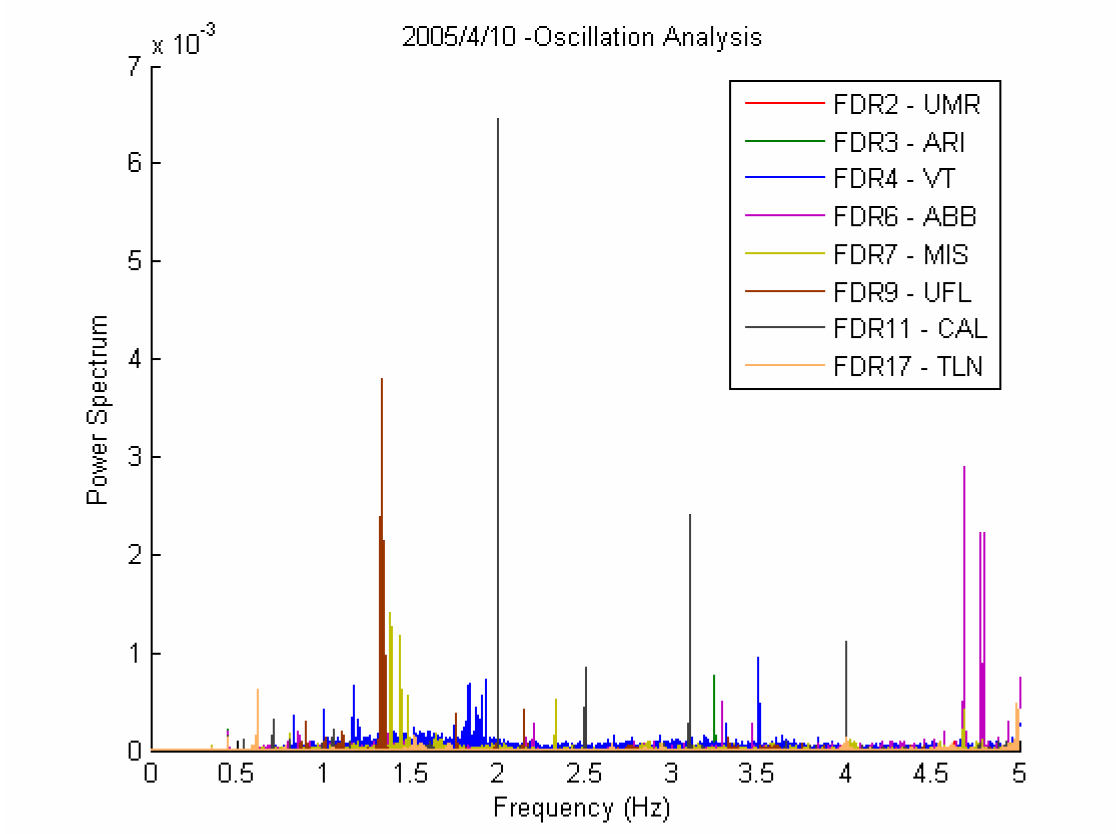



Figure C.8 Spectrum Analysis of Frequency Oscillation on Apr. 10, 2005

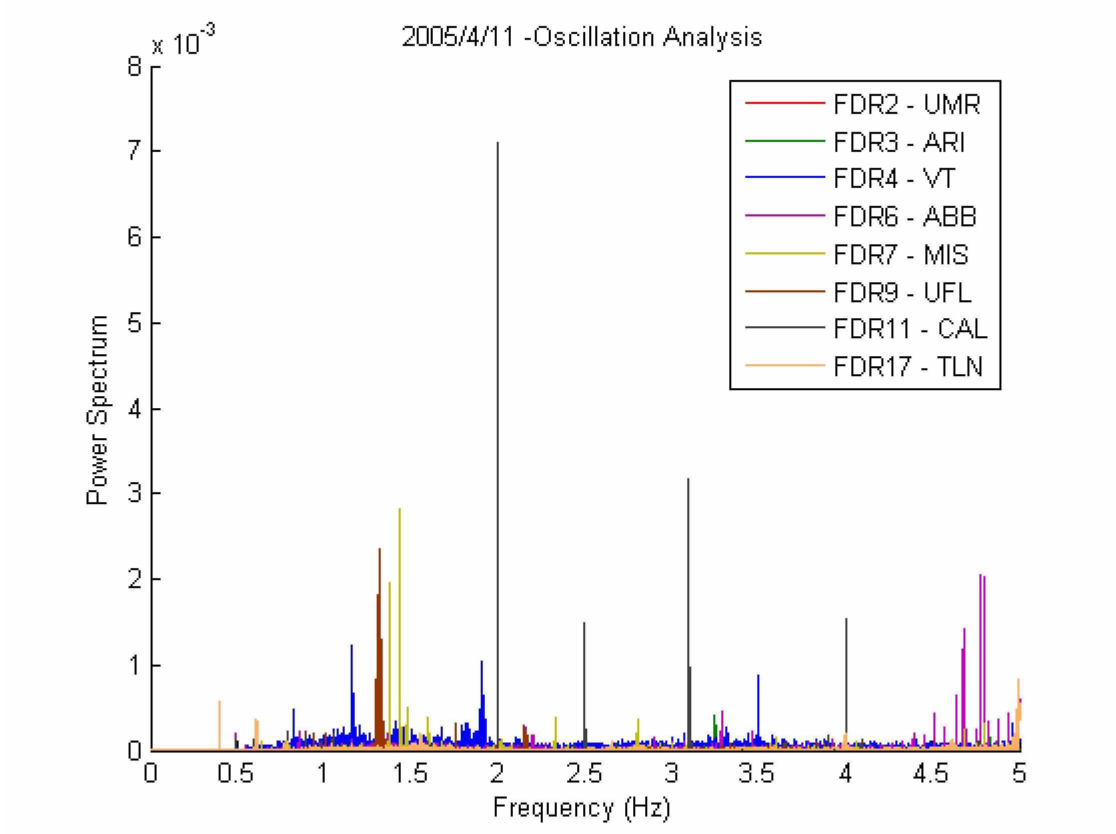



Figure C.9 Spectrum Analysis of Frequency Oscillation on Apr. 11, 2005

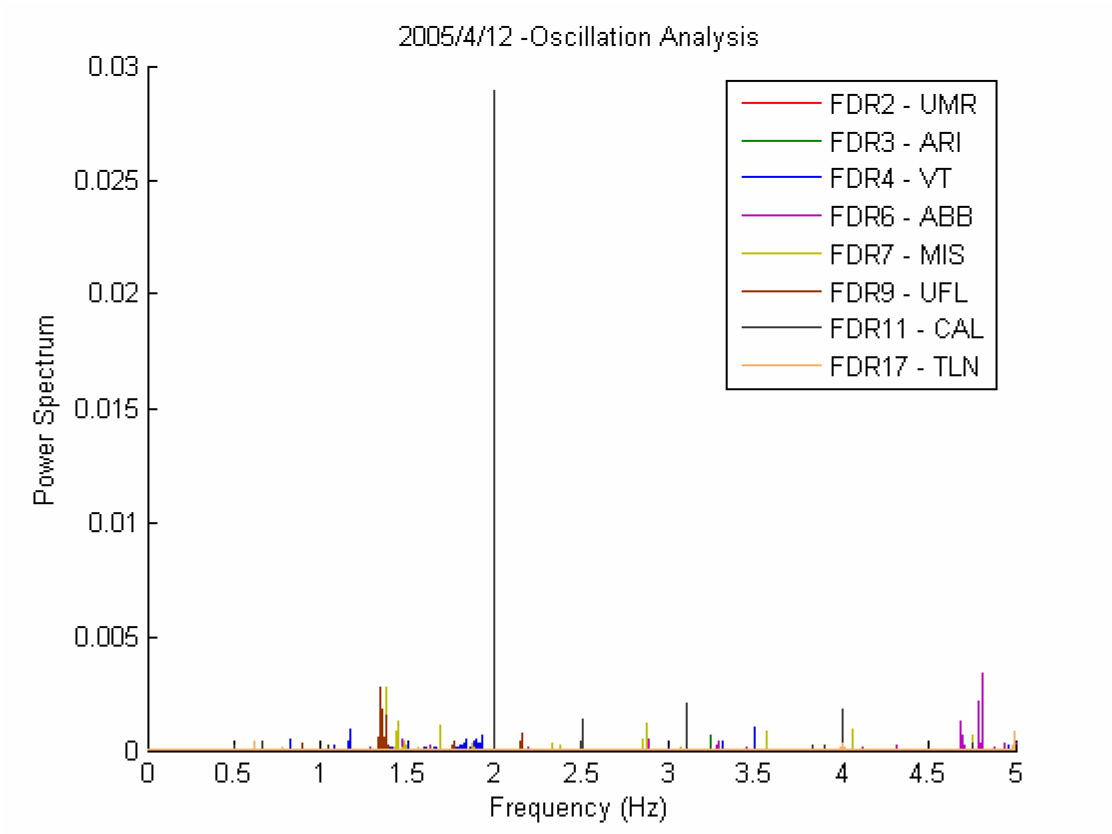



Figure C.10 Spectrum Analysis of Frequency Oscillation on Apr. 12, 2005

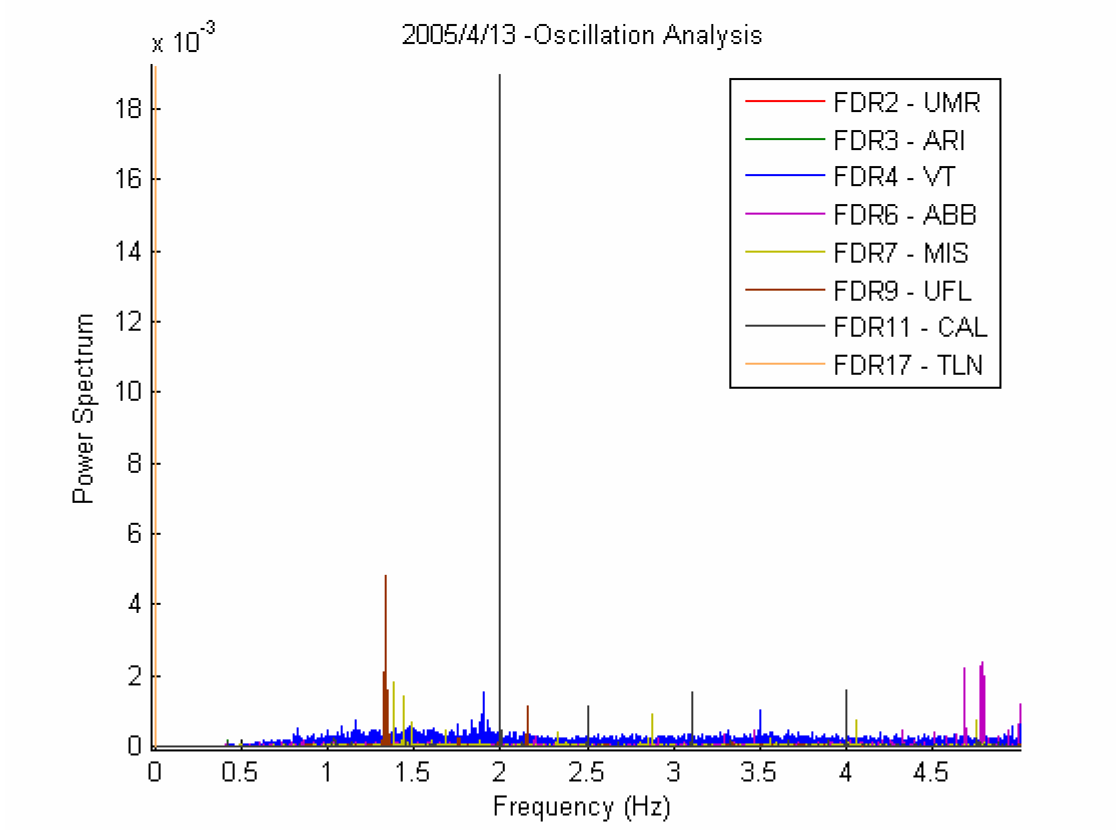



Figure C.11 Spectrum Analysis of Frequency Oscillation on Apr. 13, 2005

The plots show the oscillation mode of each unit from Apr. 2 to Apr.14, more analysis can be carried out with the same mathematical processing algorithm.

# Appendix D Disturbance Location Code in Matlab

```
clear
datapath=['C:\MATLAB7\work\'];
datafile=['davisbesse.txt'];
freq = load(datafile);
b=size(freq);
windowSize = 20;
unitNum=20;%b(1,2);
pointNum=b(1,1);
confirmevent = 0;

%read the map into matlab
figure;
grid = imread('powerline-grid.jpg');
image(grid);

%Initialization of array and memory
for i=1:1:10*windowSize
   for unit=1:1:unitNum
      FreqMem(i,unit)=0;
      counter(unit) = 0;
    %  dev(unit)=0;
   end
end
eventcounter = 1;

%Grab the data
for n=1:1:pointNum
   value = freq(n,1);
   unit  = freq(n,2);
   time  = freq(n,3);

   for i=1:1:(10*windowSize-1)
      FreqMem(i,unit) = FreqMem(i+1,unit);
   end
   FreqMem(10*windowSize,unit) = value;
   counter(unit) = counter(unit)+1;

avefreq(1,unit) = mean(FreqMem(8*windowSize+1:9*windowSize,unit));    % running
average
avefreq(2,unit) = mean(FreqMem(9*windowSize+1:10*windowSize,unit));
dev(time,unit) = avefreq(2,unit)-avefreq(1,unit);
```

```
if (counter(unit)==3*windowSize)&(time>3*windowSize)
        numarray = size(confirm_event_array);
        for k=1:1:numarray(1)
            if (unit == confirm_event_array(k,1))
                avg_post_event(unit) = mean(FreqMem(9*windowSize:end,unit)) ;
                confirm_event_array(k,6) = avg_post_event(unit);
%                 disp(['The ave Freq after event of Unit',num2str(unit), ' is:',
num2str(avg_post_event(unit)),' at:',num2str(time-0.5*windowSize)]);
                if(unit == confirm_event_array(end,1))
                    confirm_post_avefreq = mean(confirm_event_array(:,6));
                    delta_freq = confirm_pre_avefreq - confirm_post_avefreq;
                    delta_W = delta_freq * 31464;
                    disp(['The frequency change during the event is:',num2str(delta_freq),'Hz,
generation change is:',num2str(delta_W),'MW']);

                    confirm_event_array = 0;

                end
            end
        end
     end

     if (counter(unit)>3*windowSize)
            %determine whether the deviation exceeds the threshold
            if (dev(time,unit)<-0.007)

                i=time;
                while (dev(i, unit)<-.001)
                    i = i-1;
                end
                avg_pre_event(unit)=mean(FreqMem((10*windowSize-time+i-
2.5*windowSize):(10*windowSize-time+i),unit));

                disp(['Unit',num2str(unit),' Dev is: ', num2str(dev(time,unit)), ' at:',
num2str(time),' start from:',num2str(i),' average pre_event freq is:
',num2str(avg_pre_event(unit))]);
                counter(unit)=0;

                %put the detected event information in array
                eventArray(eventcounter, 1) = unit;         %unit ID
                eventArray(eventcounter, 2) = dev(time,unit);    %Deviation value
                eventArray(eventcounter, 3) = time;            %sequence Number, time
                eventArray(eventcounter, 4) = avg_pre_event(unit);    %pre_event average
frequency
                eventArray(eventcounter, 5) = 1;                %event end time find flag
```

```
            %find out whether other units detect the event in 5 seconds
            if eventcounter>1
                for k=1:1:eventcounter-1
                    deltaTime = time-eventArray(k,3);
                    if (deltaTime<3*windowSize)&(unit-eventArray(k,1))
                        confirmevent = confirmevent + 1;
                        for i=1:1:5
                            confirm_event_array(confirmevent,i)=eventArray(k,i);
                        end
                    end
                end
                if confirmevent==5
                    for i=1:1:5
                        confirm_event_array(confirmevent+1,i)=eventArray(eventcounter,i);
                    end
                    confirm_pre_avefreq = mean(eventArray(:,4));
                    disp([num2str(confirmevent+1),'units confirmed event!!! ave
is:',num2str(confirm_pre_avefreq)]);

                    drop_sequence = confirm_event_array(:,1);
                    for i=1:1:confirmevent
                        deltaTime(i) = confirm_event_array(i+1,3)-confirm_event_array(i,3);
                    end
                    drop_sequence = drop_sequence'
                    deltaTime = deltaTime/10
                    %gen(1,:)=[5202.2 1764.9]; %Watts_Bar
                    gen = [5276.6 2803.4]; %Davis_Besse
                    demoLocation(drop_sequence, deltaTime, gen);
                end
                confirmevent = 0;
            end
            eventcounter = eventcounter + 1 ;

        end
    end
end
```

# VITA

## Zhian Zhong

Personal

Date of Birth: October 22, 1978
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Education

Ph.D. Electrical Engineering, 2005
Virginia Polytechnic Institute and State University, Blacksburg, VA
Dissertation: "Power Systems Frequency Dynamic Monitoring System Design and Applications"

M.S. Electrical Engineering in Power System, 2003
Tsinghua University, Beijing, China
Thesis: "Study of Power System Wide Area Power Angle Measurement System"

B.S. Electrical Engineering in Power System Automation, 2000
Tsinghua University, Beijing, China
Thesis: "Graphical Interfaces and Communication in Real-time Decision-making System for Power System"

Professional Experience

- Graduate Research Assistant 08/2003 -06/2005
  Power IT Lab, Virginia Tech, Blacksburg, VA

1. Implementation of the project: power system frequency monitoring network Tuning the program of Frequency Disturbance Recorder (FDR). Involved in tuning the hardware design of Frequency Disturbance Recorder. Programming the server code to receiving the data sending from FDR through Internet and storage the data to the database. Designing the web server to display the data online.
2. Under Frequency Load Shedding (UFLS) new algorithm design based on wide-area frequency information
3. Frequency Information Analysis with data from FNET

- Graduate Research Assistant 07/2000 -06/2003
  State Key Laboratory of Control and Simulation of Power System and Generation Equipment, Tsinghua University, China

1. Participating in the project "Research on collapse prevention and optimal operation of the large-scale power systems in china", supported by National 973 Key Basic Research Special Fund of China.

2. Involved in the project "South Grid Power System Voltage Stability Analysis". Studying power system analysis software package of VSAT (Voltage Stability Assessment Tool), TSAT (Transient Stability Assessment Tool) and BPA, making the system simulation and analysis of the power system in four provinces in south China, which is a very large power system including HVDC and AC transmission lines, with VSAT,TSAT and BPA

• Senior Research Assistant *09/1999-07/2000*
Power System Simulation Laboratory, Tsinghua University, China

1. Power system monitoring system design, programming communication software to connect the client and server computer and graphical interface of the server to handle data

Publication

Zhian Zhong, Cheng Lin, Sun Yuanzhang, "Study on global measurement of transient power angle and dynamic simulating experiment", Automation of Electric Power Systems, 2002(No.16), in Chinese.

Peng Jiangnan, Zhian Zhong, Sun Yuanzhang "Power system hybrid simulator for transient stability analysis and emergency control based on real-time wide area measurement", Power Systems and Communications Infrastructures for the future, Beijing, 9/2002.

Zhian Zhong, Cheng Lin, Sun Yuanzhang, "A Novel PMU Configuration and Application in Real-time Transient Stability Analysis and Emergency Control", Proceedings on International Power Engineering Conference (IPEC 2003), Singapore, May 27-29, 2003.

Yilu Liu, S.-J. S. Tsai, Zhian Zhong, "Frequency Dynamic Behavior of Large Power Systems", in 2nd International Conference on Critical Infrastructures, Grenoble, France,2004.

Zhian Zhong, C. Xu, B. J. Billian, S.-J. S. Tsai, R. W. Conners, V. A. Centeno, A.G. Phadke, Y. Liu, "Power System Frequency Monitoring Network (FNET) Implementation," IEEE Transactions on Power Systems, (accepted, in press).

S.-J. S. Tsai, Z. Zhong, J. Zuo, "Frequency Analysis of Bulk Power Systems from Wide Area Measurements" (In progress)

Zhian Zhong, Yilu Liu, "Study on event location and estimation of generation change in generator tripping event", (in progress)

Technical report

Zhian Zhong, Yilu Liu, “FNET server design and under frequency loading shedding research based on wide-area information”

Zhian Zhong, Yilu Liu, “Estimation of event location and tripped generation of generator tripping fault based on FNET frequency information”