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## **Wide-Area Frequency Monitoring Network (FNET) Architecture and Applications**

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### **SUMMARY**

Recent developments in smart grid technology have spawned interest in the use of phasor measurement units to help create a reliable power system. Wide-area monitoring systems (WAMSs) utilizing synchrophasor measurements can help with understanding, forecasting, or even controlling the power grid in real-time. A power system Frequency Monitoring Network (FNET) was first proposed in 2001 and was established 2004. As a pioneering WAMS, it serves the entire North American power grid through advanced situational awareness techniques, such as real-time event alerts, accurate event location estimation, animated event visualization, and post event analysis.

Several papers published in the past several years discussed the FNET structure and its functionality. This paper presents some of the latest implementations of FNET's applications, which add significant capabilities to this system for observing power system problems.

### **KEYWORDS**

Frequency Monitoring Network (FNET), Frequency Disturbance Recorder (FDR), Synchrophasor, Phasor Measurement unit (PMU), Wide Area Monitoring System (WAMS), Global Positioning System (GPS)

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## I. INTRODUCTION

GPS time-synchronized phasor measurements [1]-[4] were introduced in the mid-1980's. Since a Virginia Tech research team developed the first prototype PMU in 1988, PMUs have been gradually, but cautiously deployed throughout the North American power system. The initial field installations of the PMUs were in the service territories of Bonneville Power Administration, American Electric Power, and the New York Power Authority. At present, there are 105 PMUs installed in the Eastern Interconnection (EI) and 56 in the Western Interconnection (WECC).

As a member of the PMU family, the Frequency Disturbance Recorder (FDR) was developed at Virginia Tech in 2003. Thus far, there are about 200 FDRs installed in North America and another 20 deployed worldwide. Fig. 1 is a distribution map indicating the locations of all the FDRs deployed in North America. A wide-area Frequency Monitoring Network (FNET) was constructed by utilizing the FDR data collected from the three interconnections in North America. FNET has served utilities, academics, and regulators since 2004 with valuable synchrophasor data and its applications [5]-[8].

The main reason for the rapid FNET deployment is the extremely low cost and high accuracy dynamic measurements that this system makes possible. Each FDR is actually a single-phase PMU in the sense that it measures the voltage phase angle, amplitude and frequency from a single-phase voltage source. The fact that the FDRs are installed at the 120-V distribution level significantly reduces their manufacturing and installation costs. The frequency measurement algorithm in the FDRs makes use of phasor analysis and signal re-sampling techniques, which have virtually zero algorithm error in the range between 52 and 70 Hz [6]. Real hardware accuracy of the FDRs falls into the interval of  $\pm 0.0005$  Hz, which is better than certain commercial PMUs.

Frequency is a universal parameter across the entire interconnected power system [9], [10]. It can provide information about generation electro-mechanical transients, generation-demand dynamics, and system operations, such as load-shedding, breaker reclosing, and capacitor bank switching. This characteristic allows frequency monitoring to be as informative at the distribution level as it is at the transmission level. Phasor calculation in the FDRs is derived from real-time voltage signal sampling and its Discrete Fourier Transform-based complex representation. Voltage phase angles and magnitudes are also measured by FDRs, which can provide useful information for power system event recognition and status estimation.

This paper reviews the basic structure of the FNET system from both the system's physical framework and the data utilization perspective. Finally, the state-of-the-art FNET applications are presented and discussed in detail.



Fig. 1. Map of FDR locations in North America

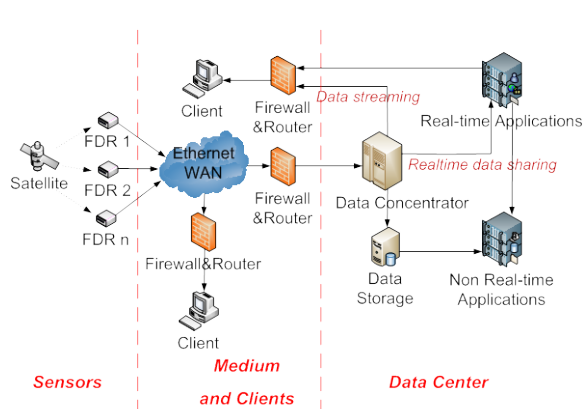


Fig. 2. Structure of the FNET system

## II. FNET STRUCTURE

Fig. 2 demonstrates the key components of the FNET system. Phasor measurements from the North American power grids are collected by widely installed sensors, known as Frequency Disturbance Recorders (FDRs), and are transmitted via the Internet to a local client or remote data center. In most

cases, FDR data are transmitted to the FNET data center for processing and long-term storage.

Each FDR is equipped with a GPS receiver, which is used to provide the accurate time signal needed for synchrophasor calculation. The units are powered from ordinary 120-V electrical outlets, which also provide the voltage signal used to compute the phasor value. Internet access is required in order for FDRs to transmit their measurement results. They are installed in a variety of locations, such as power plants, substations, office buildings, and private residences.

Measurement data from FDRs are managed in the data center by multi-layer agents. The top layer is the FNET data concentrator, whose primary functions are to receive data from the FDRs, create GPS time-aligned records, share data with the real-time application agent as soon as the records are made, and forward the data records to the data storage agent and subscribed clients. The real-time application agent and data storage agent are in the second layer of the data center hierarchy. The third layer is the non-real-time application agent.

In order to discuss the uniqueness and advantages of the FNET system, it is important to introduce the sensors and data center more specifically.

#### A. Sensors (FDRs)

An FDR is an embedded microprocessor system with GPS time synchronization and Ethernet communications capability. First built in 2003 [11], [12], the FDR is now in its second generation as shown in Fig. 3. The first generation FDR was composed of a transformer, low-pass filter, analog-to-digital converter (ADC), GPS receiver, microprocessor module, and Ethernet communications module. Fig. 4 demonstrates the framework of the first-generation FDR. The second-generation FDR has been upgraded with more integrated printed circuit boards. Instead of using a single microprocessor to handle both phasor calculations and communications, the newer version implements a digital signal processor (DSP) for data calculation and a microcontroller for communications. In terms of accuracy, the newer version FDR utilizes an active filter design instead of a passive inductor-capacitor filter as in the first generation FDR. It has a sharper cut-off frequency edge, which leads to less noise allowance.



Fig. 3. Photo of the second generation FDR

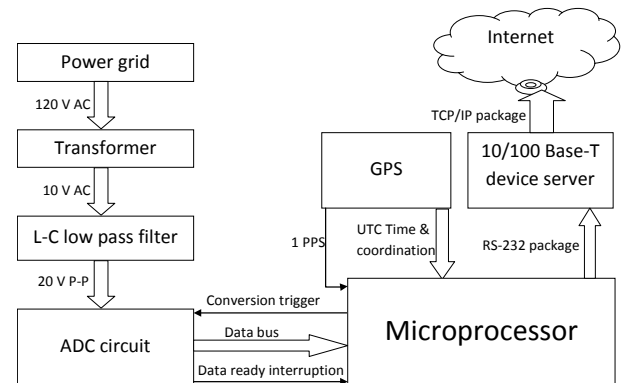


Fig. 4. First generation FDR hardware block diagram

Despite the differences in hardware layout, both generations of FDRs are driven by the same principle. A regular power outlet's 120-V sinusoidal voltage signal is stepped down to 10 V by the internal transformer of the FDR. High frequency noises are then blocked by the low-pass filter. The ADC periodically samples the 10-V signal according to the GPS clock-regulated oscillator pulses. (Oscillator pulses are synchronized with a one pulse-per-second (PPS) signal, provided by the GPS module.) Phasor values such as voltage magnitude, phase angle, and frequency are calculated by the central processing units and then transmitted over the Internet by the serial-to-Ethernet device server.

The resulting frequency accuracy of the FDRs is  $\pm 0.0005$  Hz or better. A comparison was made in 2003 between one FDR and four commercial PMUs from two different manufacturers. During the comparison period, PMUs and the FDR measured the same voltage phasor from a wall outlet. Wang et

al. in [11] concluded that the FDR's frequency measurement accuracy is more refined than that of the four commercial PMUs.

### B. Data Center

The FNET data center is a multi-layer data management and utilization system operated by several dedicated server computers. The most powerful component of the data center is the FNET data concentrator. All active FDRs send data to particular TCP/IP ports, which are then stored into a pre-defined static memory section of the data concentrator. The saved data are in the format of records; each contains all FDRs' measurements with the same GPS time stamp. Each record is streamed to the real-time application server at the time it is created. Whenever the size of the records reaches the assigned limit within the memory cache, all the records are written into a Microsoft Access database and saved in the data concentrator. The data collection and record padding are not interrupted by the saving procedure because the memory cache is designed as a stack; only the oldest portion of the data is saved. Three times per day, the most recent data is saved to a new Access database file. The data concentrator possesses the ability to flag bad data, report missing data and alarm abnormal interruptions to ensure accurate FNET operations and complete data recordings.

The second layer of the data center hierarchy is composed of the real-time application server and the data storage server. The real-time application server includes several real-time modules, such as the web-based frequency and angle displays, frequency and oscillation event triggers, and event triangulation.

The third layer is a non-real-time analysis server. Applications implemented on this server are operated on the saved data from the data storage server or the real-time application server such as event visualization, oscillation modal analysis, and web service.

## III. FNET APPLICATIONS

FNET applications [13]-[27] can be divided into real-time and non-real-time applications by their response time frame. Real-time applications require response within seconds or even sub-seconds after receiving the data while non-real-time applications have more flexible timing requirements. The FNET system defines applications that operate on the data in the memory cache as real-time and those that operate on any other saved data as non-real-time. But because the functional correspondences of the applications are not arranged by their category, it is hard to introduce them by simply dividing them into two categories.

### A. Frequency Monitoring Interface

The frequency monitoring interface module is one of the real-time applications. Fig. 5 is a screen shot of the interface window. After double-clicking the selected unit in the left column, the unit name, its IP information, connection status and a dynamic frequency plot will be displayed. Below the curve window, a dynamic data stack is also shown in the format of how it will appear in the Access database.

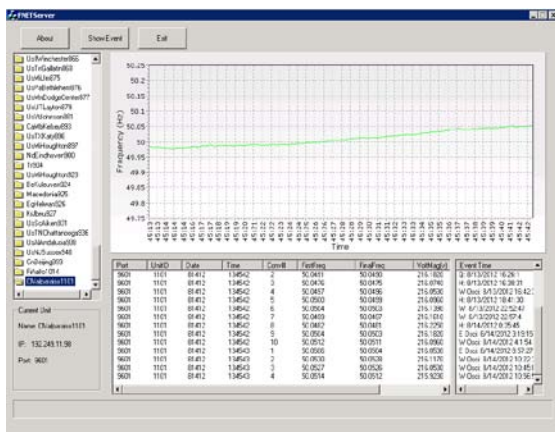


Fig. 5. The FNET frequency monitoring interface

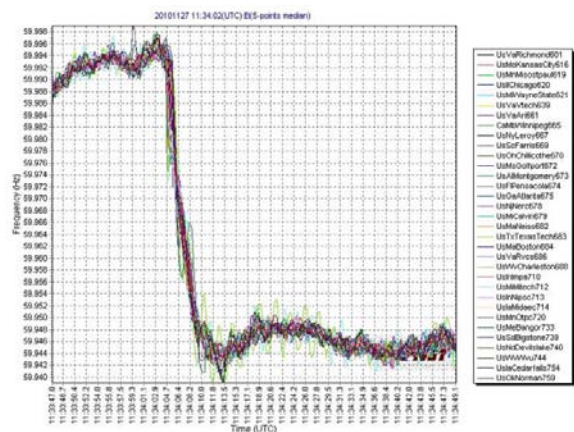


Fig. 6. An example of the generation trip event trigger (2010)

The bottom right window displays events that have been recorded by other FNET real-time

applications since the beginning of each day. The monitoring interface is not only an important tool for FNET system diagnosis, but also a platform that can be upgraded into an operation interface for the FNET system to be integrated into control centers in the future. Power system health is communicated to operators in real-time so that human intervention can be performed to prevent event cascading.

### *B. Event Trigger*

Power system frequency variation always reflects a generation and demand mismatch, either in long term or dynamic situations. The FNET event trigger module detects such phenomena by continuously scanning the incoming FDR records; thus it is located in the real-time application layer. The scanning window calculates the derivative of 10 seconds' worth of data. Whenever the calculation result exceeds a pre-defined limit, a frequency disturbance has occurred in the system.

The event trigger module then automatically sends an alarm message to the operator, records the 20 seconds of data before and after the disturbance, and records the corresponding frequency curve plot. Fig. 6 displays a typical generation loss event that is recorded by the event trigger module. Besides generation loss, a system frequency disturbance caused by load shedding could also evoke a positive response from this module.

Event time is defined to be the earliest turning point among all the FDR measurements. If the average mismatch of frequency before and after the event is represented by  $\Delta f$ , and the time that elapsed from the pre-event steady state to the post-event steady state is approximately  $\Delta t$ , the ratio of  $\Delta f / \Delta t$  is directly related to the system power mismatch during the event.

The recorded 40 seconds' worth of event data is passed on to the non-real-time layer. This action closes the event trigger module.

### *C. Event Location*

The event location module is initiated immediately following the event trigger module. Because the event location module does not operate on real-time data, and because its operation period could be in the tens of seconds, it is located in the non-real-time layer. The event location method is based on a geometrical triangulation algorithm making use of the Time Difference of Arrival (TDOA). Thorp et al. in [30] discussed the frequency disturbance propagation in the power system as a travelling wave. The propagation velocity of the disturbance is decided by the electromechanical inertia of the electrical path. Therefore, the disturbance arrival times at different measurement locations are different and can be identified by the GPS time-synchronized FDR data. The wave propagation phenomenon is observed in both frequency and angle data. Based on the wave front arrival time of different FDRs, the triangulation algorithm can determine the original location of the disturbance.

Although some error is introduced by the fact that the algorithm uses geometric distances rather than the actual electrical distances, this method has proven to be very effective and accurate given that it is extremely difficult to gather all the electric network schematics and models from the utilities. But, if such information were available, the FNET event location module could utilize it to improve the accuracy accordingly.

A U.S. patent has been issued for using frequency TDOA in locating the source of power system disturbances [27].

### *D. Inter-area Oscillation Trigger*

Power system oscillations can be associated with events such as generation trips and load shedding, but they can also be ambient. The FNET system creates a separate path for treating the oscillation data. Because of the high accuracy that FNET possesses on measuring system dynamics, power system oscillations can be monitored from both FNET phase angle recordings and FNET frequency recordings. Fig. 7 and Fig. 8 display the frequency and relative phase angle (referenced to one FDR's measurements) recordings of a 2008 event that happened in Florida. The total frequency deviation during the event is approximately 0.34 Hz; meanwhile, the total angle deviation is nearly 99 degrees. Obviously, the resolution obtained from angle deviation during system oscillation events is much higher than it is from frequency measurements. Therefore, when it comes to oscillation detection trigger design, phase angle data from FDRs are preferable.



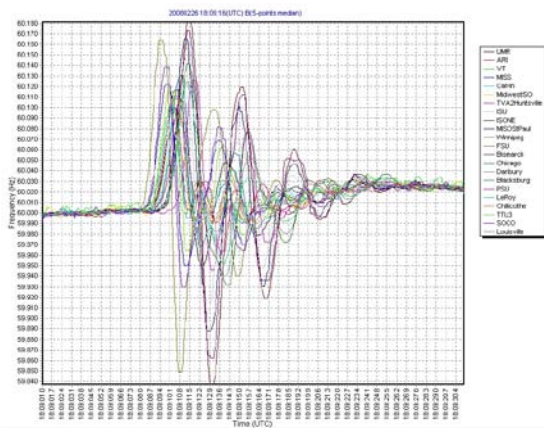


Fig. 7. Frequency oscillation monitoring by FNET

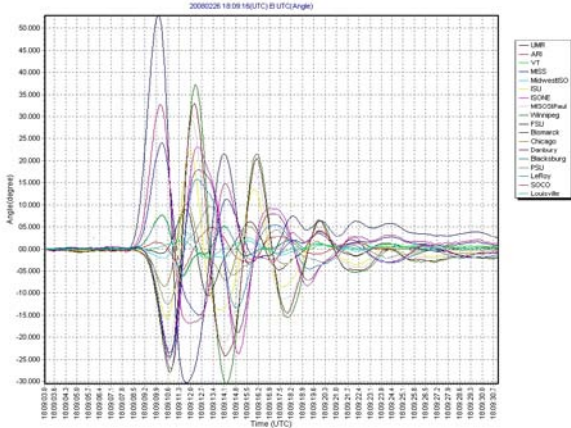


Fig. 8. Relative angular oscillation monitoring by FNET

The oscillation trigger module scans the incoming data records if they do not evoke the event trigger module. An oscillation data pattern has the signature that the first swing of the oscillation brings the angle measurements up beyond a threshold and down below another threshold or vice-versa. The detection algorithm senses when both are exceeded within a certain time interval. If the difference between the maximum and minimum value in this wave exceeds a certain limit, an oscillation is confirmed. Fig. 9 is a sample case that was captured by the oscillation trigger module.

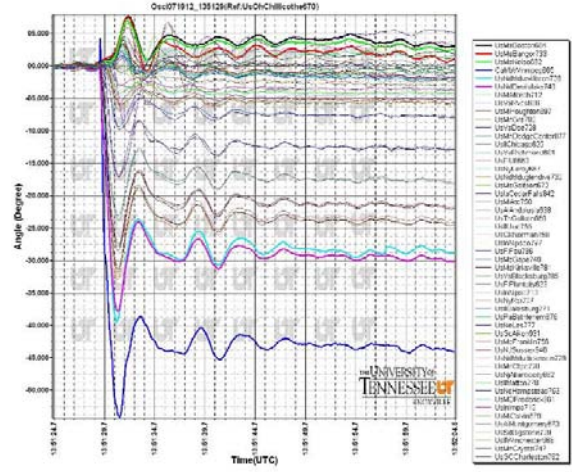


Fig. 9. Oscillation trigger sample case

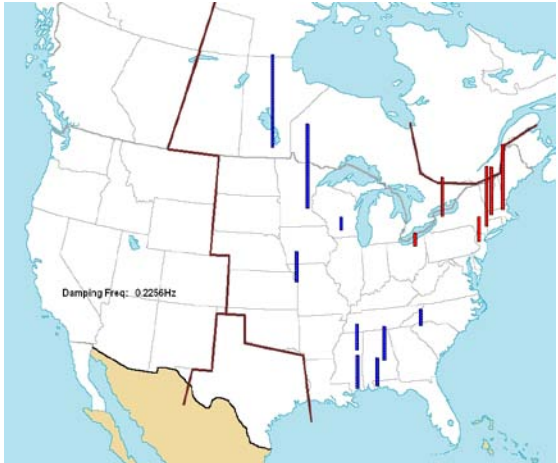


Fig. 10. Oscillation modal analysis sample case

As with the event trigger module, 10 seconds' worth of data before the start point of oscillation and 30 seconds of data after the start point are recorded and sent to the non-real-time application layer.

*E. Inter-area Oscillation Modal Analysis*

The inter-area oscillation modal analysis module, a third layer application, starts functioning after receiving oscillation data from the oscillation trigger. The Matrix Pencil approach, because of its robustness to noise, is used as the signal decomposition tool for modal analysis.

The Matrix Pencil tool utilizes wide-area FNET multi-channel data for simultaneous best match decomposition and reconstruction. The shared major modes from different monitoring locations can be identified, and the major mode amplitudes and angles can be calculated in order to form a picture of inter-area oscillation. An example is shown in Fig. 10. The colors of the bars indicate the oscillation angle direction at certain measurement points. The heights of the bars are proportional to the oscillation magnitudes. The major mode in this case that is shared by all the monitoring locations is 0.226 Hz.

From the map display it is obvious that in this case the EI system is divided into two parts: the north-eastern and north-western parts oscillate together against the south-eastern part. According to

statistical analysis based on the FNET oscillation database, severe oscillations always show up in those three geographical regions, which indicates a lack of damping in those parts of the power system.

It is believed that the system inter-area oscillation modes could vary significantly if the system topology, load distribution, and power flow are changed. Modal analysis utilizing the FNET database can provide the critical parameters at each particular system operation state.

### F. Event Visualization

Frequency disturbance events have a geographically distributed impact, as the electromechanical waves propagate throughout the power system in time and space. It is therefore beneficial for the grid operators to have intuitive visualization of the cascading response.

The FNET event visualization module reads an event data file, generates a color-coded frequency deviation matrix and links it with geographical coordinates on a U.S. map. A series of these maps are then combined to generate the event movie. Fig. 11 shows screen captures from a generation trip event movie created from FDR frequency measurements. This event occurred in the Eastern Interconnection on April, 27, 2011, when all three units at TVA's Browns Ferry Nuclear Power Plant tripped offline. The amount of generation lost was approximately 3,500 MW, causing the interconnection frequency to drop to 59.90 Hz.

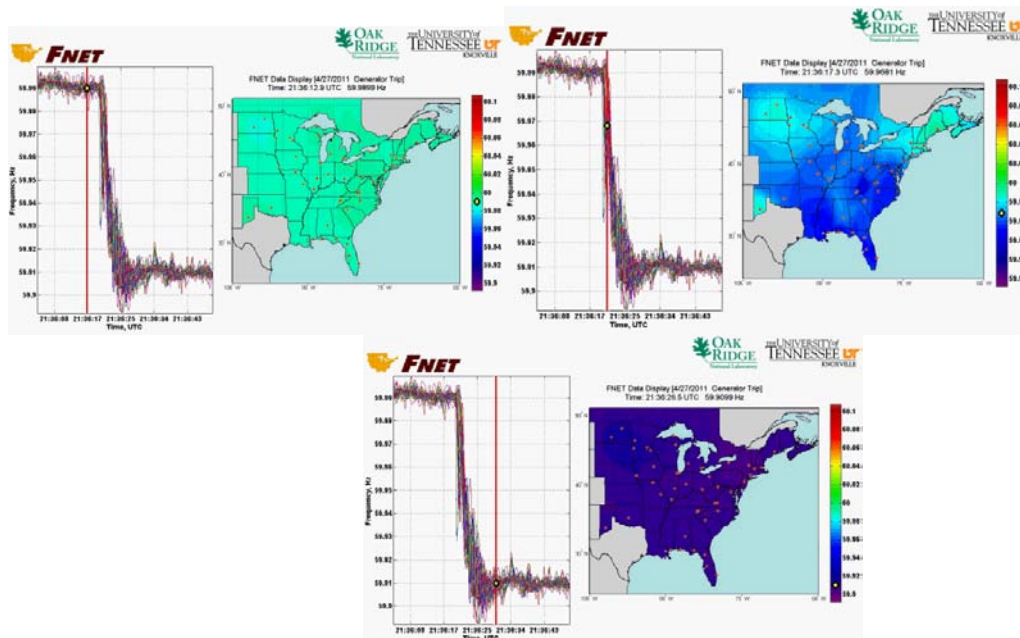


Fig. 11. Generation trip event movie screen shots before, during and after the event

### G. Web Display

The FNET web display integrates visualization components such as a frequency table display, map display, and map gradient. It provides an educational platform for researchers, grid operators and regulators to better understand the power system status from a wide-area perspective. Fig. 12 shows a screen shot of the frequency table display. The data shown are dynamically updated at a lower rate than the data transmitted from the FDRs in order to reduce the website server load.

Frequency Color Scheme (60 Hz nominal)										
	<59.90	59.90-59.95	59.95-59.99	59.99-60.01	60.01-60.05	60.05-60.10	>60.10	No Data		
Eastern Interconnection Units (60 Hz nominal)										
UTC Time	00:52:15	00:52:11	00:52:07	00:52:03	00:51:59	00:51:55	00:51:51	00:51:47	00:51:43	00:51:39
UsVaRichmond601	59.9887	59.9877	59.9878	59.9878	59.9885	59.9874	59.9904	59.9936	59.9968	59.9957
UsMoKansasCity616	59.9881	59.9884	59.9879	59.9883	59.9882	59.9873	59.9901	59.9934	59.9967	59.9969
UsMnMisostpaul619	59.9868	59.9879	59.9885	59.9868	59.9878	59.9876	59.9907	59.9930	59.9970	59.9978
UsIlChicago620	59.9882	59.9877	59.9880	59.9871	59.9886	59.9874	59.9908	59.9939	59.9966	59.9963
UsMiWayneState621	59.9885	59.9874	59.9880	59.9880	59.9885	59.9870	59.9903	59.9937	59.9964	59.9960

Fig. 12. Screen capture of the web-based FNET frequency table display.

### H. Line Trip Detection and Identification

Line trip events are local-area phenomena that are typically not observable system-wide. Frequency at the sending end of the tripped line will rise due to the generators' acceleration, whereas frequency will drop at the receiving end of the line due to machine deceleration caused by the generation deficit. The pre-outage power flow on the line will be redistributed to the remaining lines in the system, which causes bus angle changes. Fig. 13 and Fig. 14 show frequency and angle excursions of a 500-kV line outage in the EI.

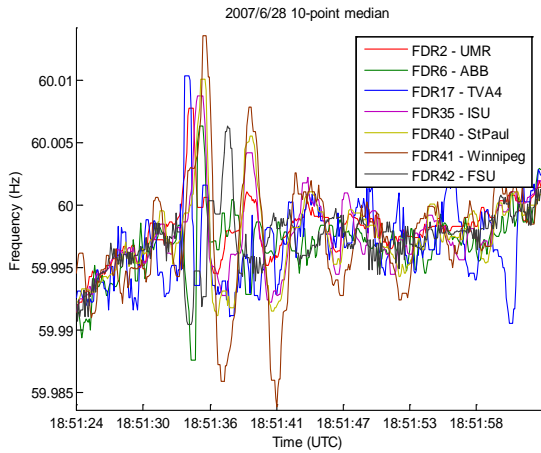


Fig. 13. Frequency excursions of a line trip event in EI

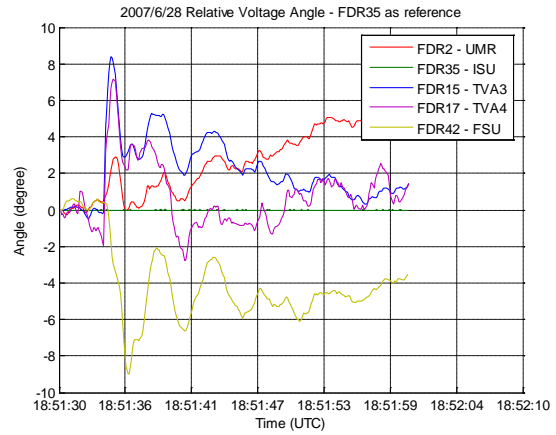


Fig. 14. Relative angle for a line trip event (FDR35 as reference)

With the advantages of low cost and high-accuracy measurements, it is highly likely to achieve high-density FDR deployment, which is desirable for line trip detection and identification. Line trip detection tools have been developed based on both frequency and phase angle measurements obtained by FNET. The frequency-based line trip trigger detects a line trip event by triggering on the frequency excursion peaks, whereas the angle-based tool captures the sharp changes in relative angle due to a line outage.

Outage of a certain transmission line has its unique signature as a combination of frequency and angle changes measured by FDR units. Therefore a line outage library can be constructed based on both simulation data and real measurements. A line trip can be identified by matching the features extracted from real measurements with those in the line outage case library. A line trip identification algorithm has been developed that locates a line outage based on this methodology as a tool for further analysis.

### I. Other Applications

Some FNET applications have been developed, but have not yet been implemented in the FNET system, such as islanding detection, which will be introduced in this chapter briefly.

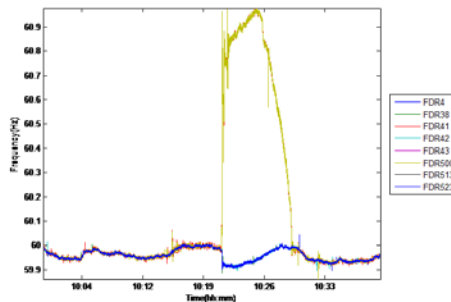


Fig. 15. Islanding example from the FNET database



Power system islanding is a rare phenomenon occurring when one or more generators are no longer working synchronously with the rest of the system. Fig. 15 shows a system islanding event that happened on September 17<sup>th</sup>, 2007 in the EI system when part of the system lost synchronization with the rest but still supplied load within its islanded region for about nine minutes. This event initiated the study of islanding detection using FNET data.

There are tools developed based on frequency variation rate and signature to detect islanding by the Power Information Technology Laboratory. In the future they will be implemented as real-time applications in the FNET system.

### J. FNET Applications Summary

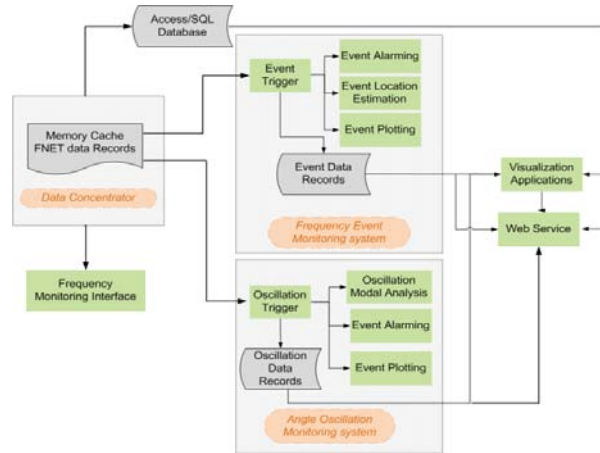


Fig. 16. FNET application hierarchy and data flow paths.

Fig. 16 demonstrates the overall FNET application hierarchy and data flow paths. The FNET application system is modularized so that it is fairly easy to rearrange any particular element in the hierarchy. For example, the visualization module is now a human command-driven module that is fed by the data storage server. In the future, it will be implemented as an automatic module invoked by the event and oscillation triggers. It will read data from the text file data records and generate a movie for each case. New applications can also be easily implemented due to the modular design of the FNET application system.

## IV. CONCLUSION

The FNET system was originally built as a power grid WAMS specifically applied to frequency monitoring. However, its GPS-synchronized phasor measurement capability also allows parameters such as the angle difference to play an important role in power system situational awareness. The FNET system hierarchy has been well designed for high volume data transfer, processing, storage and utilization. A variety of applications, especially with regards to real-time dynamic monitoring, have been developed and integrated into the system. FNET is growing into a mature, multifunctional, low-cost phasor measurement system with stable performance and high accuracy.

The FNET system's potential for power system dynamic monitoring, stability estimation, real-time control and smart grid solutions are currently being explored.

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