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A Distribution Level Wide Area Monitoring System for the Electric Power Grid–FNET/GridEye

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ABSTRACT The wide area monitoring system (WAMS) is considered a pivotal component of future electric power grids. As a pilot WAMS that has been operated for more than a decade, the frequency monitoring network FNET/GridEye makes use of hundreds of global positioning system-synchronized phasor measurement sensors to capture the increasingly complicated grid behaviors across the interconnected power systems. In this paper, the FNET/GridEye system is overviewed and its operation experiences in electric power grid wide area monitoring are presented. Particularly, the implementation of a number of data analytics applications will be discussed in details. FNET/GridEye lays a firm foundation for the later WAMS operation in the electric power industry.

INDEX TERMS Dynamics, power grids, phasor measurement units, wide area measurements.

I. INTRODUCTION

Electric power systems are probably the most critical infrastructure of modern society. Due to their extreme vastness and complexity, it is difficult for them to be fully monitored and reliably controlled. Based on the new data acquisition technology of phasor measurement, wide area monitoring system (WAMS) measures the electrical waveforms at multiple power grid nodes using a common time source, providing the grid operators unprecedented system monitoring and control opportunities.

The sensors used to perform the wide area phasor measurement are known as phasor measurement units (PMUs), which originated from the research on computer-based relaying of transmission lines in 1977. Due to the limited computational capability at that time, Arun et.al at Virginia Tech proposed the symmetrical component algorithm for transmission line relaying [1] and, along with this algorithm, presented an efficient method to calculate the positive sequence components of voltage and current, which are referred to as power system phasors. These phasors serve as the fundamental state attributes of the power system and are essential in most power system analysis and calculations. Most importantly, the launching of Global Positioning System (GPS) at that time provided an effective approach to synchronize the phasor measurements over a large geographical area [2], [3]. As a result, the first GPS-synchronized PMU prototype was invented in 1988 and then the first commercial PMU product was built in 1992. Since PMUs are able to benefit the power system operators significantly by monitoring system status and detecting different disturbances etc., the importance of PMUs and WAMS have been gradually recognized by the electric power industry [4].

In the past ten to twenty years, many individual WAMS applications have been proposed in the literature, such as disturbance detection [5], [6], oscillation analysis and damping control [7], and state estimation [8]. Some of the individual applications have even been demonstrated in the field and proven to be highly effective in improving power system stability [9]–[12]. However, due to the high cost of installing a large number of phasor measurement sensors and the immaturity of certain applications, the electric utilities have been cautious in the wide WAMS implementations.

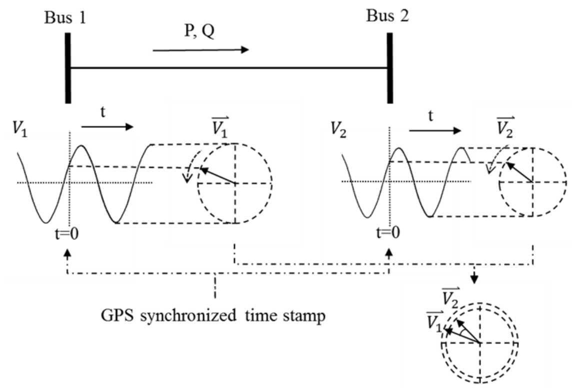


FIGURE 1. Synchronized phasor representations of sinusoid waveforms.

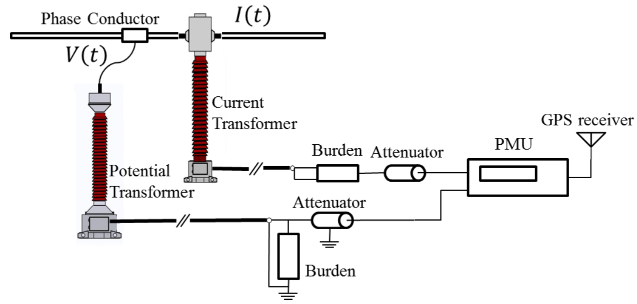


FIGURE 2. PMU installation and connection diagram.

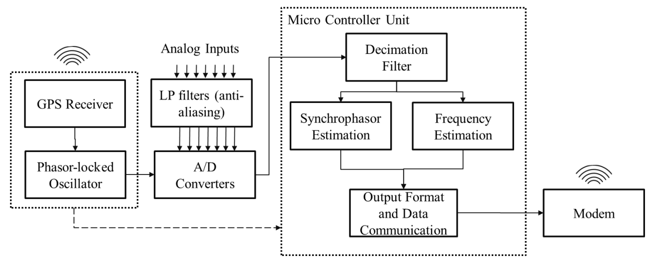


FIGURE 3. PMU hardware architecture.

Obviously, a pilot WAMS will be extremely beneficial to the future WAMS development since it can showcase the effectiveness of newly developed applications and provide valuable first-hand operation experiences.

The frequency monitoring network FNET/GridEye was developed against this background [13], [14]. It has been operated by the University of Tennessee, Knoxville (UTK) and Oak Ridge National Laboratory (ORNL) and its mission is to pioneer and promote the WAMS technologies in electric power utilities. Up to now, FNET/GridEye has already developed a serial of PMU data-driven applications to process, visualize, and analyze the streaming and stored measurement data from hundreds of WAMS devices [15]. The online FNET/GridEye applications are able to analyze the real-time streaming data arriving from multiple sensors while the offline applications work only upon request for the archived data analysis. All these applications are designed to interpret the constantly changing grid operation status for the system operators and increase their situational awareness capabilities. In this paper, after a brief introduction of phasor measurement, the FNET/GridEye system will be introduced and its representative applications will be discussed in more details.

II. PHASOR MEASUREMENT

The concept of phasor measurement and the basics of PMUs will be introduced in this section. Fig. 1 shows the sinusoidal voltage waveforms at both the sending and receiving ends of a transmission line and their phasor representations $\vec{V}_1$ and $\vec{V}_2$. Using Fast Fourier Transform (FFT) or Discrete Fourier Transform (DFT), these two phasors can be calculated. Most importantly, sharing the same time source from GPS satellites, these two phasor representations can be time-stamped and sent to the control room respectively from two different locations. Therefore, though they may not arrive at the control room simultaneously due to different communication delays, they can still be aligned and compared thanks to the same GPS time reference. Apparently, a comparison between $\vec{V}_1$ and $\vec{V}_2$ won't be meaningful without this time synchronization.

PMUs are currently installed at the high-voltage substations or large power plants. Since there are three phases involved, each PMU will require three connections that measure all three phases for both current and voltage. A diagram of the typical PMU installation on one phase at a substation is shown in Fig. 2. The current transformer (CT) and potential transformer (PT) scale down the current and voltage of the high voltage buses in order to fit the input ranges of the A/D converters in the PMU. The burdens in Fig. 2 represent the VA rating of the electronic instruments connected to the PT/CT secondary circuits and the attenuators are used for adjusting the output amplitudes further. Due to the relatively high installation costs of PTs and CTs, PMUs are installed only at the most important nodes of the power system right now.

A typical PMU device's hardware architecture and functionality components are shown in Fig. 3. The analog inputs from CT and PT will first go through a low-pass anti-aliasing filter. The basic anti-aliasing strategy is to use an analog filter that has a cut-off frequency slightly higher than the Nyquist criterion while another strategy is to use a much higher sampling rate and then add a digital 'decimation filter' in addition to the analog filter. In this case, the cut-off frequency of the analog filter will be much higher than the Nyquist criterion. It has been found out that a combination of analog and digital filters makes the filtering performance more robust to aging and temperature changes. In addition, the high sampling rate can increase the phase calculation precision potentially and even enable the PMUs to act as the digital fault recorders if enough memory is available. The calculations of voltage and current phasors, as well as frequency and rate of change of frequency (ROCOF) estimation, are performed by the

FIGURE 4. Generation-II FNET/GridEye sensor.

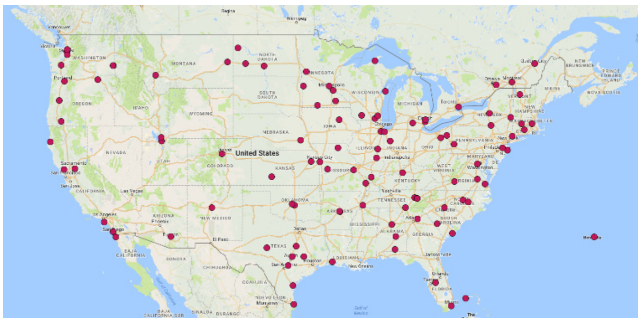


FIGURE 5. FNET/GridEye sensor locations in North America.

FIGURE 6. World-wide FNET/GridEye sensor deployment.

micro controller unit and then all the measurement results are time-stamped, packaged, and transferred to the control room via the communication links.

III. FNET/GridEye OVERVIEW

As a member of the phasor measurement family, FNET/GridEye is developed as a pilot wide-area phasor measurement system that can cover the national or continental level power grid at a much lower cost before the universal PMU installations can be achieved. In this section, the FNET/GridEye system is briefly overviewed.

A. FNET/GridEye SENSOR

In order to achieve the phasor measurement at as many locations as possible, the FNET/GridEye sensor was designed to be deployed at the low voltage distribution grid instead of

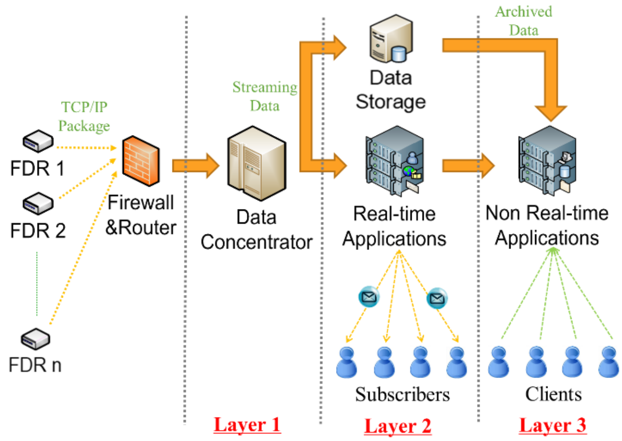


FIGURE 7. Architecture of the data center.

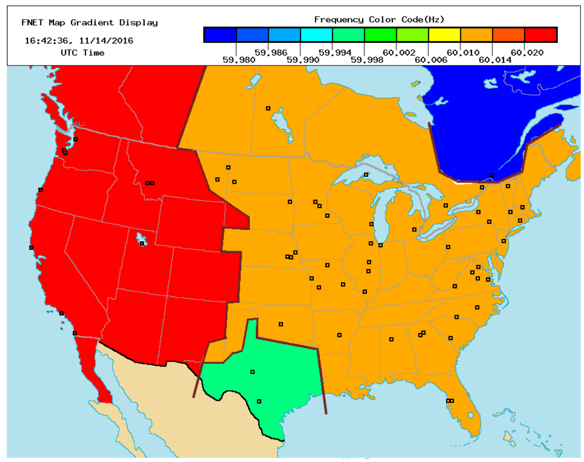


FIGURE 8. FNET/GridEye real-time frequency visualization (snapshot).

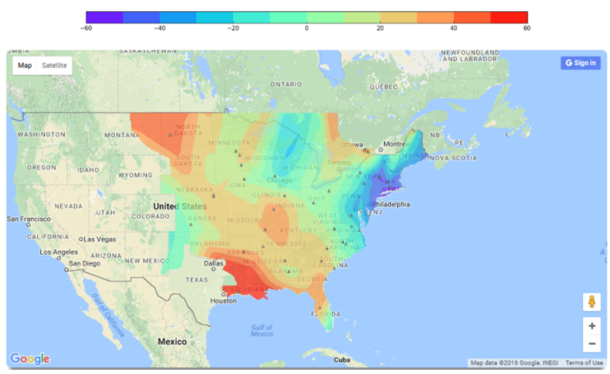


FIGURE 9. FNET/GridEye real-time voltage angle visualization (snapshot).

high voltage substations or power plants [16]. Therefore, the high-priced PTs and CTs for typical PMUs can be waived and the installation cost of a FNET/GridEye sensor can be reduced to only tenth of a typical PMU. Nevertheless, there are some extra technical challenges associated with the phasor measurement in the distribution grid. One example is that, different from the high voltage transmission systems with relatively fewer harmonics, distribution grids have much worse

Basic Event Information							
Event Date	2016-11-14	Event Time	09:54:34 UTC	Event Type	Generation Trip	Estimated Amount	1100 MW
Point A	59.9998 Hz	Point B	59.9597 Hz	Point C	59.9572 Hz	Point C Prime	59.9588 Hz
InterConnection	EI	Estimated Reliability Coordinator		SERC		ROCOF	7.16 mHz/s
Estimated Event Location	(38.7497, -85.035)	Additional Location Information		near Ghent power plant (SERC) in (Ghent,KY,41045).			

Event Data Plots
(Click Images to View in Full Size)

Frequency plot of All FDRs | Location Map

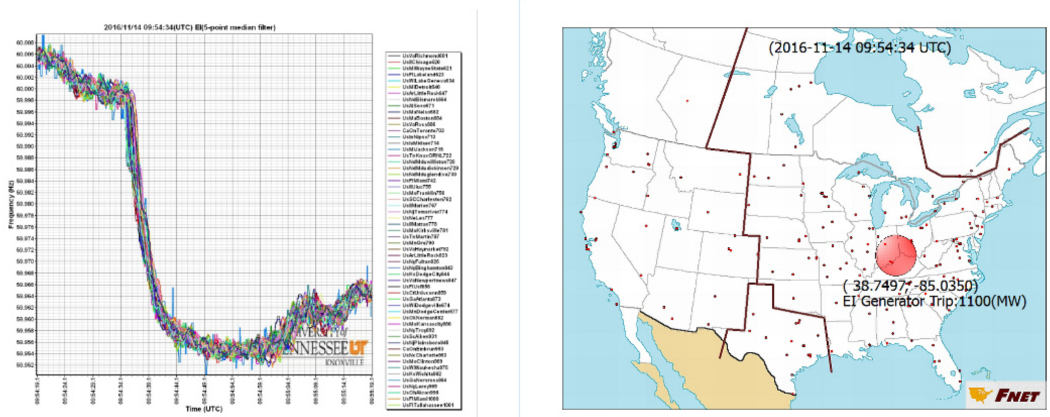


FIGURE 10. **Example of the FNET/GridEye disturbance detection report.**

power quality due to the harmonics and distortions produced by various electric appliances at the customer side. Therefore, extra effects have been used to develop the advanced algorithms that can achieve the accurate phasor measurement in the noisy environments [17]–[20].

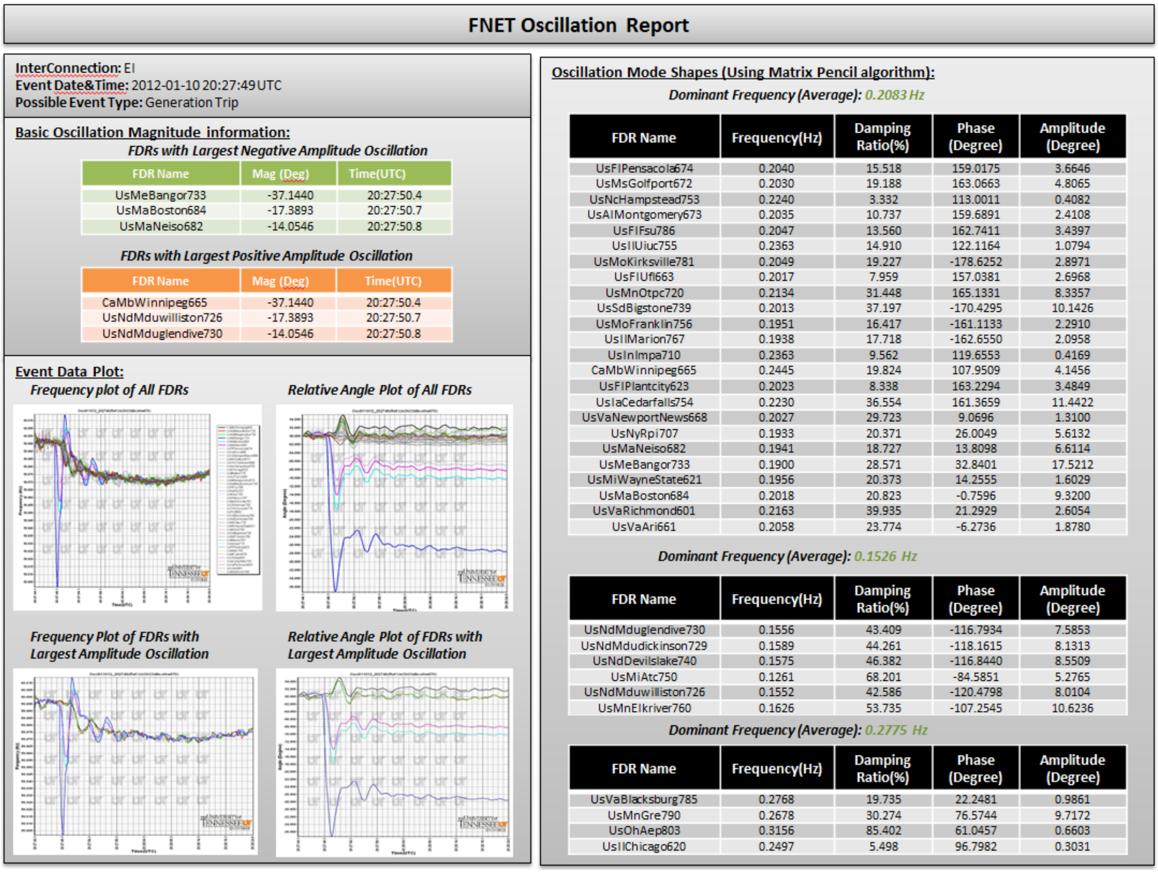
Three generations of FNET/GridEye sensors have been developed since 2003 in order to improve measurement accuracy and add more measurement functions. Fig. 4 shows the Generation-II FNET/GridEye sensor which is the most widely deployed so far. Its measurement accuracy reaches ± 0.0005 Hz in terms of frequency and ± 0.0002 rad in terms of voltage angle. Furthermore, to mitigate the impact of GPS signal loss on the accuracy and reliability of the sensors, chip scale atomic clock has been tested on the FNET/GridEye sensors [21].

The North American and worldwide deployment of FNET/GridEye sensors by 2016 are shown in Fig. 5 and Fig. 6, respectively. The real-time phasor measurements collected by the hundreds of FNET/GridEye sensors at the indicated locations are transmitted via Ethernet and collected by the data centers hosted at both UTK and ORNL. These measurements allow multiple power grid status monitoring and analysis functionalities, including grid status visualization, online disturbance detection, and offline data mining etc.

B. FNET/GridEye DATA CENTER

Employing a multi-layer architecture, the FNET/GridEye data center is designed to receive, process, utilize, and archive a large volume of phasor measurements in real-time [22]. Its main structure is shown in Fig. 7.

The first layer of the data center is the data concentrator, where the measurement data packages are extracted and forwarded to the subsequent layers. The bad data will also be labeled and abandoned here. The second layer includes two agents: the storage agent and the real-time application agent. Various FNET/GridEye real-time application modules are running on the real-time application agent to monitor power grid status by scanning the data streaming in. For example, on this agent, the real-time disturbance detection module sends out alerts to system operators once it detects the occurrence of a disturbance. Meanwhile, the data storage agent archives phasor measurement data streams and outputs from the real-time application agent for off-line applications. All the data are archived in an efficient format to preserve data integrity while saving space. At the third layer, the non-real-time application agent runs offline applications to further exploit the archived data. For example, the dynamic models of U.S. power grids could be validated through comparing the actual system frequency responses (stored in the archived



FNET Oscillation Report

InterConnection: EI
Event Date&Time: 2012-01-10 20:27:49 UTC
Possible Event Type: Generation Trip

Basic Oscillation Magnitude information:

FDRs with Largest Negative Amplitude Oscillation

FDR Name	Mag (Deg)	Time(UTC)
UsMeBangor733	-37.1440	20:27:50.4
UsMaBoston684	-17.3893	20:27:50.7
UsMaNeiso682	-14.0546	20:27:50.8

FDRs with Largest Positive Amplitude Oscillation

FDR Name	Mag (Deg)	Time(UTC)
CaMbWinnipeg665	-37.1440	20:27:50.4
UsNdMduwilliston726	-17.3893	20:27:50.7
UsNdMduglendive730	-14.0546	20:27:50.8

Event Data Plot:

Oscillation Mode Shapes (Using Matrix Pencil algorithm):

Dominant Frequency (Average): 0.2083 Hz

FDR Name	Frequency(Hz)	Damping Ratio(%)	Phase (Degree)	Amplitude (Degree)
UsFlPensacola674	0.2040	15.518	159.0175	3.6646
UsMsGolfport672	0.2030	19.188	163.0663	4.8065
UsNcHampstead753	0.2240	3.332	113.0011	0.4082
UsAlMontgomery673	0.2035	10.737	159.6891	2.4108
UsFlFsu786	0.2047	13.560	162.7411	3.4397
UsIlUiuc755	0.2363	14.910	122.1164	1.0794
UsMoKirksville781	0.2049	19.227	-178.6252	2.8971
UsFlUfl663	0.2017	7.959	157.0381	2.6968
UsMnOtpc720	0.2134	31.448	165.1331	8.3357
UsSdBigstone739	0.2013	37.197	-170.4295	10.1426
UsMoFranklin756	0.1951	16.417	-161.1133	2.2910
UsIlMarion767	0.1938	17.718	-162.6550	2.0958
UsInImpa710	0.2363	9.562	119.6553	0.4169
CaMbWinnipeg665	0.2445	19.824	107.9509	4.1456
UsFlPlantcity623	0.2023	8.338	163.2294	3.4849
UsIaCedarfalls754	0.2230	36.554	161.3659	11.4422
UsVaNewportNews668	0.2027	29.723	9.0696	1.3100
UsNyRpi707	0.1933	20.371	26.0049	5.6132
UsMaNeiso682	0.1941	18.727	13.8098	6.6114
UsMeBangor733	0.1900	28.571	32.8401	17.5212
UsMiWayneState621	0.1956	20.373	14.2555	1.6029
UsMaBoston684	0.2018	20.823	-0.7596	9.3200
UsVaRichmond601	0.2163	39.935	21.2929	2.6054
UsVaAri661	0.2058	23.774	-6.2736	1.8780

Dominant Frequency (Average): 0.1526 Hz

FDR Name	Frequency(Hz)	Damping Ratio(%)	Phase (Degree)	Amplitude (Degree)
UsNdMduglendive730	0.1556	43.409	-116.7934	7.5853
UsNdMdudickinson729	0.1589	44.261	-118.1615	8.1313
UsNdDevilslake740	0.1575	46.382	-116.8440	8.5509
UsMiAtc750	0.1261	68.201	-84.5851	5.2765
UsNdMduwilliston726	0.1552	42.586	-120.4798	8.0104
UsMnElkriver760	0.1626	53.735	-107.2545	10.6236

Dominant Frequency (Average): 0.2775 Hz

FDR Name	Frequency(Hz)	Damping Ratio(%)	Phase (Degree)	Amplitude (Degree)
UsVaBlacksburg785	0.2768	19.735	22.2481	0.9861
UsMnGre790	0.2678	30.274	76.5744	9.7172
UsOhAep803	0.3156	85.402	61.0457	0.6603
UsIlChicago620	0.2497	5.498	96.7982	0.3031

FIGURE 11. FNET/GridEye oscillation detection and analysis report.

phasor measurements) with the model-produced simulation results. The multi-layer structure of the FNET/GridEye data center facilitates the concentrating, processing, and archiving of a large volume of phasor measurements so as to successfully meet the timeliness requirements of various applications.

IV. ONLINE APPLICATIONS OF FNET/GridEye

As mentioned earlier, the FNET/GridEye data analytics applications can be roughly classified into online and offline two categories by their response time requirements. Online applications such as disturbance detection require the data processing and utilization to be completed within seconds or even sub-seconds while offline applications do not have such time requirement [15], [23]. In this section, a number of critical FNET/GridEye online applications are introduced and some of the offline applications will be presented in the next section.

A. REAL-TIME GRID STATUS VISUALIZATION

Real-time grid status visualization is one of the most important and mature WAMS applications. Correlating the phasor measurement streaming in real time with PMU locations and grid topology, this application can present the visualization of system stresses through deviations in voltage angle and frequency. With respect to the FNET/GridEye, by displaying hundreds of channels of WAMS measurements from FDRs as well as their corresponding geographical location information, the real-time visualization of the U.S. power grid frequency and voltage angle can be achieved.

Fig. 8 shows a snapshot of the real-time frequency display of different U.S. power grids while Fig. 9 presents a snapshot of the real-time voltage angle display of the U.S. Eastern Interconnection (EI). These real-time displays are also available on the FNET/GridEye website. Since any frequency and voltage angle deviation indicates a system operation status change, this web-based application helps system operators capture the most recent variations of the grid status. It is the first time the entire U.S. power grid's real-time status can be visualized.

B. DISTURBANCE DETECTION, RECOGNITION AND LOCATION

The top priority of system operators is to keep the system safe from various disturbances, such as generator loss and transmission lines fault. To counteract a severe disturbance that occurs in the power grid, the initial step is the detection, recognition, and location of such a disturbance in the shortest time frame.

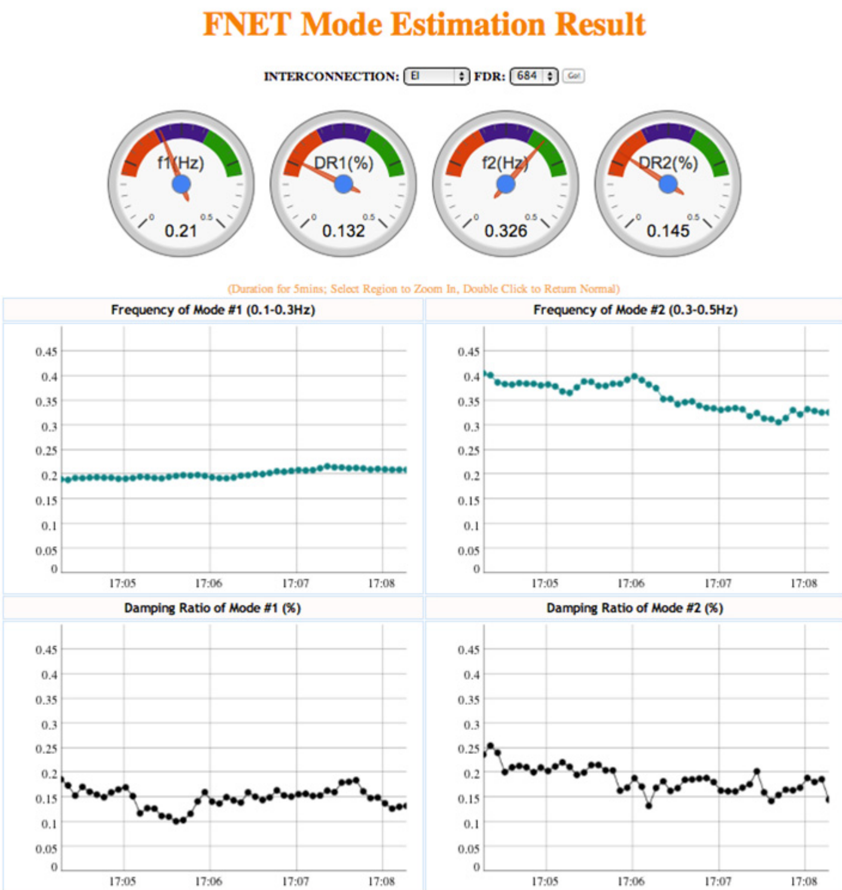


FIGURE 12. **FNET/GridEye real-time oscillation analysis visualization (ambient data based).**

Since any significant disturbance will be reflected by a sudden frequency change, this application scans the streaming frequency measurement data from different locations in real time to look for any abrupt frequency change. Specifically, this FNET/GridEye disturbance detection application calculates the rate of average frequency change df/dt continuously and a disturbance will be considered detected if a pre-defined df/dt threshold is exceeded.

Once a disturbance is detected, it will be classified into different categories, such as generation loss and load shedding, based on its unique frequency characteristics and then its location will be calculated by use of a geometrical triangulation algorithm. This triangulation method basically makes use of the time difference of arrival (TDOA) between different sensors and employs the least square algorithm to estimate the disturbance location [24], [25].

Furthermore, if the disturbance is recognized as a generation loss, the net active power loss ΔP will also be calculated by multiplying the system frequency deviation Δf during the disturbance and the historical coefficient beta value β. The frequency nadir and settling frequency will also be calculated according to the North American Electric Reliability Corporation (NERC) guidelines. Most importantly, all these detection, recognition and location results will be complied in a FNET/GridEye disturbance report (as shown in Fig. 10) and sent out automatically via an email to utility operators. Dozens of electric power utilities in the U.S. are receiving this kind of report.

C. DETECTION AND ANALYSIS OF INTER-AREA OSCILLATIONS

Inter-area oscillations pose severe threats on the power grid stability and have to be damped as soon as possible to avoid blackouts. In order for a prompt and effective oscillation damping control, the oscillations need to be detected and analyzed in the fastest manner. Since inter-area oscillations always involve different areas of the power grid, WAMS is the perfect tool to detect and analyze them. Continuously calculating the maximum frequency or angle changes within a time frame, if more than one FNET/GridEye sensors' calculation results exceed a certain threshold, an oscillation will be considered to occur and the oscillation analysis module will be started. Making use of a multi-channel matrix pencil method [26], the analysis results of each oscillation, which includes oscillation magnitude, dominant mode frequency, and damping ratio etc., can be obtained. As shown by Fig. 11, once the oscillation analysis is done, an oscillation report will be automatically sent out to system operators.

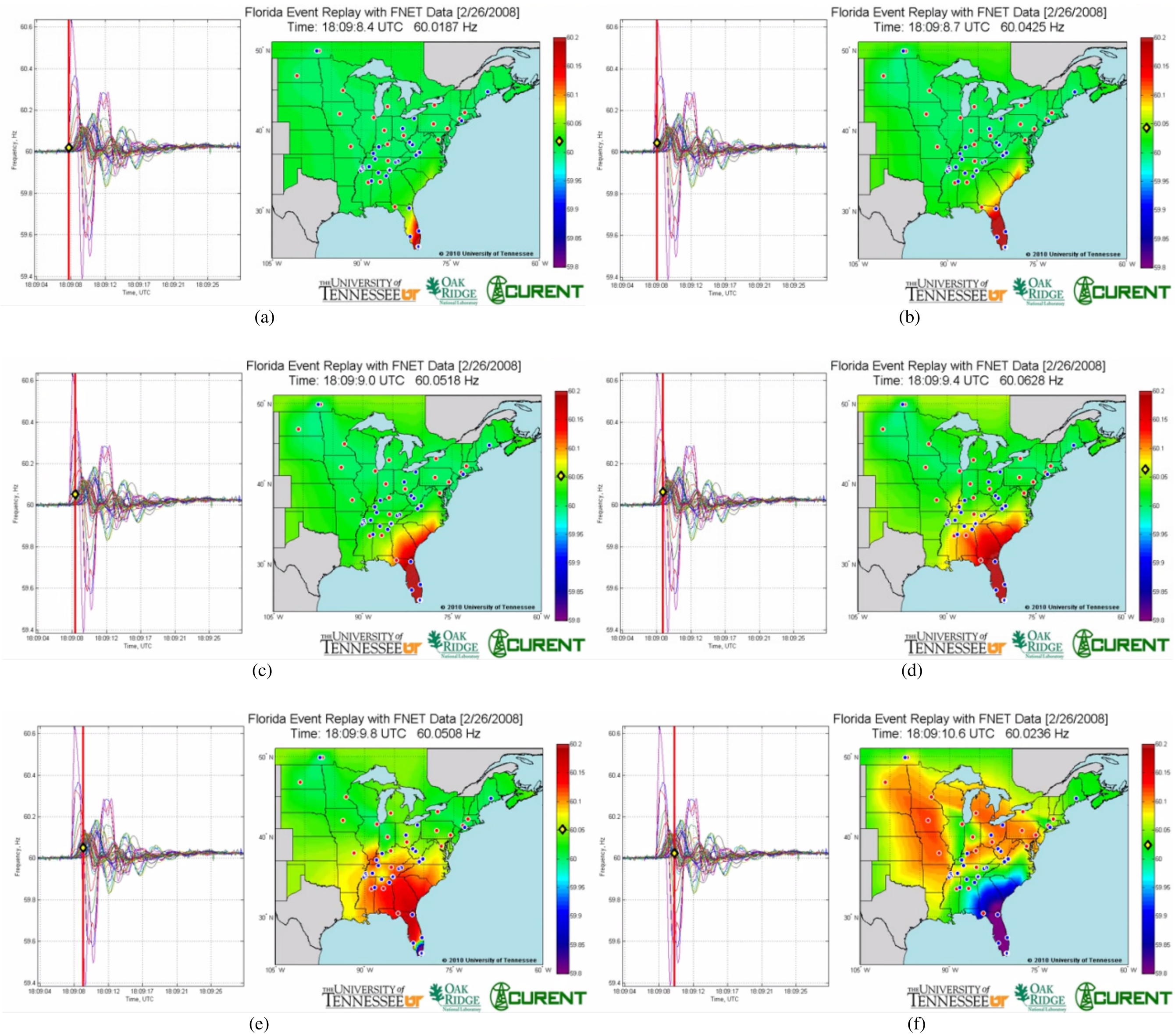


FIGURE 13. Snapshots of the 2008 Florida blackout replay.

Under ambient conditions, the power system is operating in a steady state where no significant oscillations are occurring. Though in the steady state, there still exist small variations of system parameters because of small disturbances and random load changes etc. Despite the associated signal processing difficulties, valuable oscillation modal information can still be extracted from the measurement of those small variations. The FNET/GridEye ambient data mode estimation function includes basically two steps: the first step is using the empirical mode decomposition (EMD) method to de-trend the ambient measurement signal; and the second step is to utilize the auto-regressing moving-average (ARMA) model method to perform the modal analysis [27], [28]. One thing should be noted is that this function is designed in a way that it can process hundreds of channels of streaming FNET/GridEye sensor measurements in parallel at the same time. This capability enables the visualization of a large power grid's oscillation information at multiple locations for the first time. An example of the oscillation analysis results is given in Fig. 12.

V. FNET/GridEye OFF-LINE APPLICATIONS

In the past ten years, FNET/GridEye has accumulated a large volume of measurement data. Therefore, besides the online applications discussed earlier, FNET/GridEye also developed several offline applications. Three of them will be introduced in this section.

A. DISTURBANCE REPLAY AND POST-DISTURBANCE ANALYSIS

Large scale blackouts impact the power supply over a wide area and can cause disastrous economical losses. Taking the

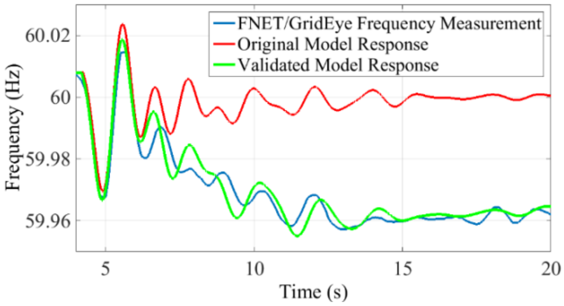


FIGURE 14. FNET/GridEye frequency measurement model validation.

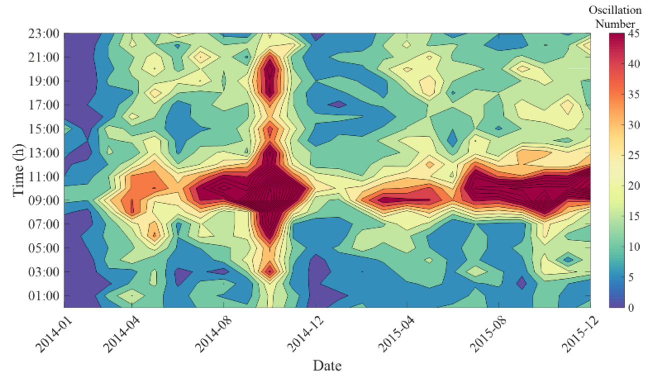


FIGURE 15. Oscillation occurrence and distribution of EI system in 2014.

2008 Florida blackout as an example, due to the loss of 22 transmission lines and 4,300 MW of generation, most of the Florida area customer loads were temporarily cut off. After such a big blackout, the operators and regulators are eager to find out its root causes in order to prevent similar events in the future. To help with that, the FNET/GridEye measurements were utilized to replay this Florida disturbance event in a video, the snapshots of which are given in Fig. 13. The abrupt frequency change caused by this disturbance was firstly observed in Florida as shown in Fig. 13 (a), and then it quickly propagated throughout the entire EI system in several seconds after the disturbance. This replay video was used in this severe disturbance's post-event analysis and contributed to the prevention of similar blackouts in the future. Many other videos of similar events can be found on the FNET/GridEye website.

B. MODEL VALIDATION USING MEASUREMENT

Model validation is another WAMS application badly needed by the electric utility industry. An accurate power system model, especially a dynamic model that describes relatively fast power system behaviors related to its stability, is essential to ensuring a power system's stability and preventing power outages. However, current power system dynamic models are inaccurate and because of its inaccuracy, some applications of the traditional model are ineffective or even impossible. To address this challenge, the frequency measurements from FNET/GridEye can be utilized to validate the power system dynamic model. In Fig. 14, after tuning several generator parameters such as machine inertia and governor settings using the FNET/GridEye frequency measurement as the benchmark, the model's simulated frequency response is able to match the frequency measurement to a much better extent [29], [30]. This serves as a good example of how FNET/GridEye can be used in system model validation.

C. HISTORICAL DATA MINING

Applying data mining techniques to the big amount of historic measurement data collected by FNET/GridEye can provide another layer of valuable power system operation information. For example, a statistical analysis of major inter-area oscillations in EI was conducted. Total 12,238 inter-area oscillations in EI with dominant mode between 0.1 and 1.2 Hz were investigated. Analysis results on the oscillation occurrence and dominant frequency for year 2014 and 2015 are presented in Fig. 15.

From Fig. 15, it can be seen that most oscillations happened between 8:00 AM and 12:00 PM UTC time. It can also be observed that in 2014 and 2015 the majority of oscillations occurred between July and November. This information will provide guidance for system operators in preventing oscillations. Some other examples of historical FNET/GridEye data analytics include the frequency extrema analysis [31], inertial frequency response analysis [32], and social event impacts on power grid [33] etc.

VI. CONCLUSION

In this paper, the FNET/GridEye was introduced as a pilot electric power grid WAMS system. As shown by this paper, FNET/GridEye has accumulated rich operation experiences in the past decade which has benefited the phasor technology development in the electric power industry. In order to further explore the potential WAMS applications, FNET/GridEye will continue to increase its sensor accuracy and develop more data analytics applications for power system status monitoring and stability enhancement purposes. FNET/GridEye will significantly promote the field implementation of WAMS-enabled applications in the electric power industry.

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