Recent Developments of FNET/GridEye — A Situational Awareness Tool for Smart Grid

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***Abstract*—Wide-area monitoring systems (WAMS) are becoming increasingly vital for enhancing power grid operators' situational awareness capabilities. As a pilot WAMS that was initially deployed in 2003, the frequency monitoring network FNET/GridEye uses GPS-time-synchronized monitors called frequency disturbance recorders (FDRs) to capture dynamic grid behaviors. Over the past ten years, a large number of publications related to FNET/GridEye have been reported. In this paper, the most recent developments of FNET/GridEye sensors, data centers, and data analytics applications are reviewed. These works demonstrate that FNET/GridEye will become a cost-effective situational awareness tool for the future smart grid.**

***Index Terms*—Distribution level, frequency disturbance recorder (FDR), phasor estimation, situational awareness, synchrophasor, wide-area monitoring system (WAMS).**

I. INTRODUCTION

Wide area monitoring system (WAMS) is a relatively new power system situational awareness tool that uses phasor measurement units (PMUs) to provide real-time, GPS-time-synchronized measurements of grid status at high data rates (two orders of magnitude beyond traditional grid telemetry) [1], [2]. Since it reveals unprecedented insights into power system dynamics, WAMS is seen as significantly improving power system operators' situational awareness capabilities, especially in the context of the smart grid.

Originally developed in 2003, the frequency monitoring network FNET/GridEye is a wide-area phasor measurement system that covers a nation-level power grid [3]–[5]. It uses low-cost high-accuracy frequency disturbance recorders (FDRs) to collect power grid frequency, voltage magnitude, and voltage phase angle, and an advanced data center to receive, process, and store all the measurements. Compared to its counterparts, FNET/GridEye is unique in several aspects: First, it takes the voltage at standard 120-V electrical outlets as the signal input. This customer-side single-phase design enables its plug-and-play feature and minimizes manufacturing cost and installation effort. Second, FNET/GridEye achieves higher measurement accuracy than its transmission and distribution level counterparts. Last and most importantly, FNET/GridEye has developed and implemented a large number of data visualization and analytics functions, which include functions that perform real-time analysis as data streams arrive from FDRs, and functions that work off-line for analyzing archived data. All these functions are designed to help grid operators interpret the power grid operation status and take proactive measures to prevent blackouts.

FNET/GridEye has been widely welcomed by academia, industry, as well as governments, and serves more than 20 main power grids in the world as of 2016. Fig. 1 shows the current FDR installation locations in North America. Please note that all the phasor measurement data collected by FDRs are transmitted to the FNET/GridEye server hosted at the University of Tennessee, Knoxville (UTK), and Oak Ridge National Laboratory (ORNL) for preprocessing, conditioning, storage, and applications.

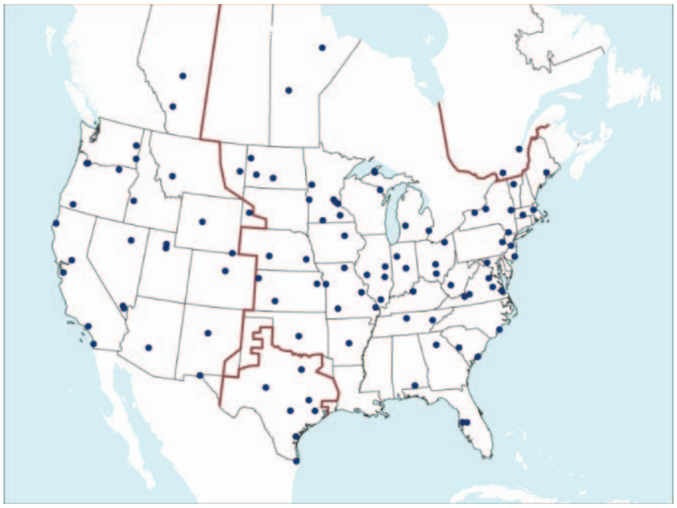

Fig. 1. Map of FDR locations in North America.

In this paper, the recent developments of the FNET/GridEye sensor and server design will be reviewed, and then some of

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the state-of-the-art FNET/GridEye applications will be presented. The paper is structured as follows: Section II introduces the latest FDR sensor designs; Section III describes the innovative FNET/GridEye data center architecture; selected applications of FNET/GridEye are presented in Section IV; and Section V concludes the paper.

II. FNET/GRIDEYE SENSOR DEVELOPMENT

As of 2016, more than 250 FDRs have been deployed across North America. Fig. 2 shows a photo of the currently deployed FDRs. This generation of FDR has achieved the steady-state accuracy of ±0.00006 Hz for frequency and ±0.005° for voltage angle measurement with a manufacture cost only tenths of traditional PMUs. Its dynamic performance has also been tested and verified [6]–[8]. Generally, an FDR consists of a voltage transducer module, a power supply module, a GPS signal receiver module, an analog-to-digital sampling module, a digital signal processing (DSP) module, a microcontroller unit (MCU), and an internet communication module. DSP here is used to perform all the phasor calculations. Then the phasor measurements are stamped in MCU and transmitted to the FNET/GridEye server using the TCP/IP protocol. In the following subsections, a number of new sensor devices or features under development will be introduced.

Fig. 2. Photo of a current FDR device.

A. Universal Grid Analyzer

Universal grid analyzer (UGA) is a highly accurate and GPS-synchronized power grid monitoring device that combines functions of power quality analyzer and phasor measurement unit at the distribution level [9]. Fig. 3 shows the measurement errors of the UGA compared to a commercial PMU, illustrating that the UGA measurement accuracy is higher than that of this commercial PMU. It should be noted that, similar to FDR, UGA uses single phase signal for calculations while PMU uses three phase signals. In addition to phasor measurement, UGA can also perform harmonics measurement and voltage sag/swell detection.

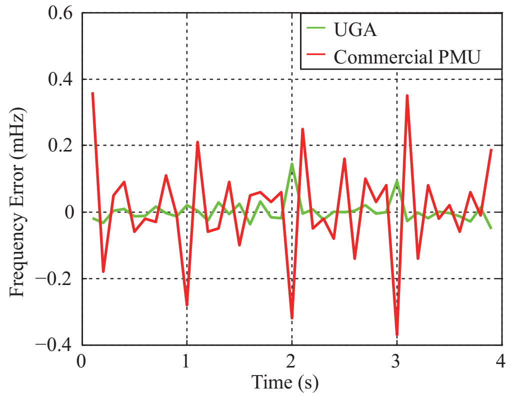


Fig. 3. Frequency errors of UGA and PMU.

B. Wireless Phasor Measurement

In conventional phasor measurement, potential or current transducers must be physically connected to buses being measured for acquiring the input signals. As phasor measurements become more widely used in power grids, there is a need for a non-contact phasor measurement device that addresses the inconvenience of setting up a traditional PMU, particularly in remote areas. Therefore, wireless magnetic and electric sensors are used to replace the conventional potential or current transducers for wireless phasor measurements [10], [11]. The illustration of such wireless phasor measurement devices is given in Fig. 4. Table I and Table II show the test results of electric and magnetic sensor based wireless PMU with different frequency inputs. It can be seen that the frequency measurement error of the wireless devices under steady-state conditions is within 0.001%. Also, the standard deviations are smaller than 0.002 Hz, which demonstrates that the steady-state frequency measurements are stable and within a narrow band, conforming to the IEEE C37.242-2013 Standard. Furthermore, to verify their accuracy in field environments, the wireless devices were tested under a 500 kV transmission line in Knoxville, Tennessee, US. Using a traditional FDR installed in the same city as a reference, the wireless devices' measurement accuracy was further verified as shown in Fig. 5.

TABLE I
FREQUENCY MEASUREMENT RESULTS OF ELECTRIC SENSOR BASED WIRELESS DEVICES

Input Signal Frequency (Hz)	Measured Average (Hz)	Relative Error (%)	STD
59.90	59.900079	0.000132	0.000825
59.98	59.980042	0.000070	0.000933
60.00	60.000081	0.000135	0.000689
60.02	60.020053	0.000088	0.000960
60.10	60.100037	0.000061	0.000928

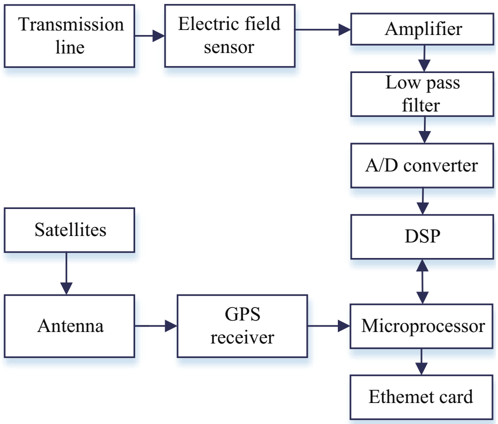


Fig. 4. The hardware structure of the E-field wireless phasor measurement.

TABLE II
FREQUENCY MEASUREMENT RESULTS OF MAGNTEIC FIELD SENSOR BASED WIRELESS DEVICES

Input Signal Frequency (Hz)	Measured Average (Hz)	Relative Error (%)	STD
59.90	59.89988	0.000115	0.001821
59.98	59.97998	0.000014	0.001986
60.00	60.000021	0.000134	0.000598
60.02	60.01990	0.000093	0.001896
60.10	60.09985	0.000147	0.001927

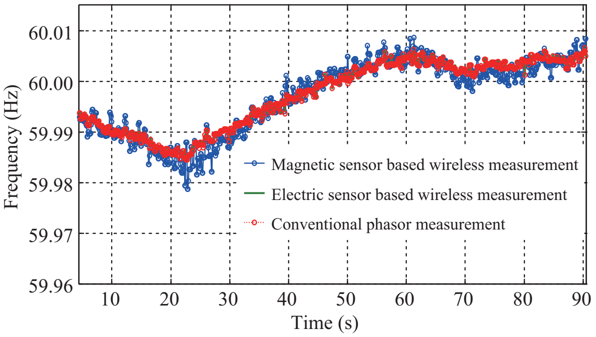


Fig. 5. Frequency measurement comparison.

C. Smartphone-based Phasor Measurement

The smartphone based FDR is a modified version of the traditional FDR. It includes a regular phone charger, a voltage transform module, a microprocessor-based analog-to-digital sampling module, and an Android-based smartphone (as shown in Fig. 6) [12]. Different from conventional phasor measurement that relies on pulse per second (PPS) signals from GPS for time synchronization, the smart phone based FDRs use Network Time Protocol (NTP) instead. Furthermore, an APP that performs the phasor measurement functions has been designed and can be easily downloaded and installed on any Android-based smartphone. One obvious advantage of this device is that its cost is minimal and it can send measurement data as long as the phone is being charged. A frequency measurement comparison to traditional FDR is shown in Fig. 7.

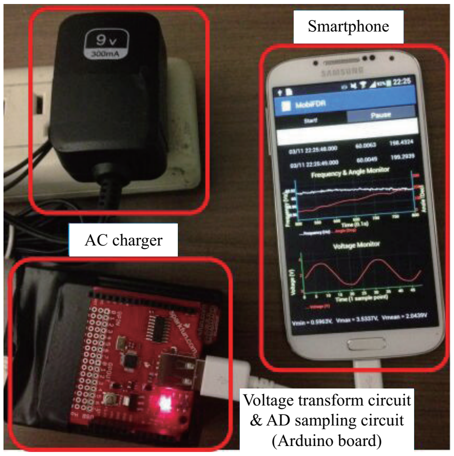


Fig. 6. Smartphone FDR diagram.

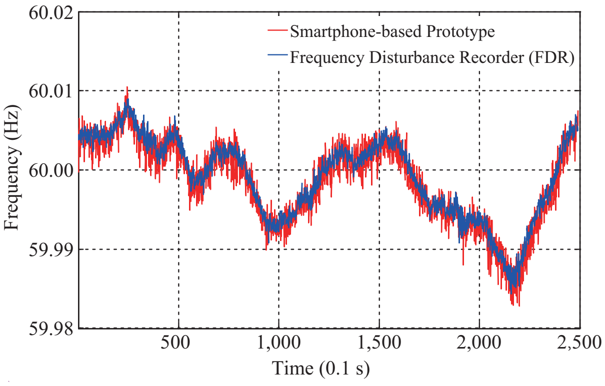


Fig. 7. Smartphone FDR frequency measurement result.

D. Chip-scale Atomic Clock (CSAC) for Timing Backup

GPS receivers within PMUs and FDRs tend to lose GPS signal from time to time due to some uncontrollable and unpredictable factors [13]. Therefore, equipping FDR with an accurate backup timing source is an effective solution to improve the reliability and security of FDRs in case GPS signals are not available temporarily. The atomic clock was not considered an option until recently because of its formidable price tag. Fortunately, the chip-scale atomic clock (CSAC) was made available and affordable for civilian use in 2011. Since then, CSACs such as Quantum$^{\text{TM}}$ SA.45s have been utilized in industrial areas that require extremely high-precision timing. In this subsection, CSAC was tested as a backup timing source for FDR [14].

Table III lists the frequency and angle measurement comparison between a traditional FDR with a GPS timing source (including a GPS receiver and an antenna) and a FDR equipped with a CSAC. The angle and frequency errors of the two FDRs are similar, which means CSAC can provide accurate timing signal for PMUs and FDRs. It should be noted that since CSAC itself does not have a timing start point, it still requires an external timing source, such as a GPS module for disciplining, which means a CSAC can only be considered as a backup, rather than a replacement of a GPS timing source.

TABLE III
STANDARD DEVIATION OF ANGLE AND FREQUENCY ERRORS OF GPS-FDR AND CSAC-FDR

Measurement Error	GPS-FDR	CSAC-FDR
Angle (degree)	0.0041	0.0046
Frequency (Hz)	1.45E-4	1.42E-4

III. FNET/GRIDEYE DATA CENTER DESIGN

The measurements collected by FDRs are transmitted to data centers at UT and ORNL where all the FDR measurement data are concentrated and processed [15]–[17]. Physically, a FNET/GridEye data center operates on several dedicated server machines, e.g. data server, application server, web server, backup server, etc. Functionally, a data center can be treated as a multi-layer data management system as shown in Fig. 8.

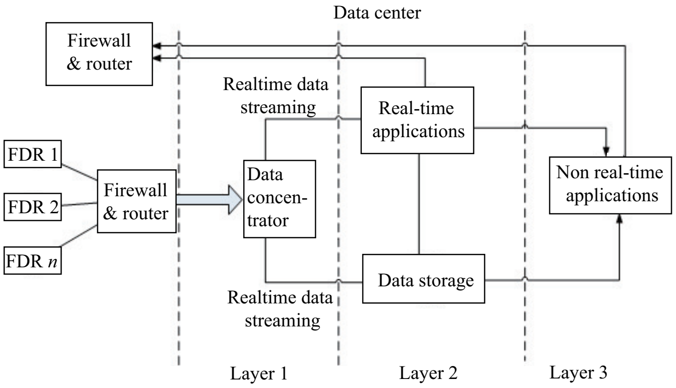


Fig. 8. FNET/GridEye data center structure.

A. Data Concentrator

The FNET/GridEye data server plays the role as a data concentrator that collects data from hundreds of FDRs around the world. Synchrophasor data are transferred to the server through TCP connections. Since the FDRs are developed as distributed level PMUs, the FDR data format is designed as a simplified version of IEEE C37.118 standard format, which only contains timestamp, frequency, angle, and voltage information measured at the distribution level, as well as the GPS coordinates of each FDR unit. The openPDC developed by Grid Protection Alliance (GPA) is tailored to adopt the FNET/GridEye data stream format, and serves as the server-side concentrator software for FNET/GridEye. Once a connection is built, the data server continuously receives the data packet, parses data to structured formats, and verifies data validity.

Even though FDRs are synchronized with GPS time, and their data packets are labeled with timestamp, the network latency from a FDR to the data server is uncertain. This requires the data server to be synchronized with an accurate clock and to be able of tolerate delay from different FDR units.

The data server is synchronized with a NTP server clock to compensate the time drift effect caused by the inaccuracy of its local clock. Other clock sources, such as atomic clock or eLoran clock, are optional to improve the timing accuracy of the server system.

The openPDC allows operators to customize the lead time and lag time parameters for the input data streams. The lead time represents the maximum time intervals that the server can accept if an arriving data packet has a timestamp ahead of the local server clock. The lag time defines the maximum time that the server can wait for the data to arrive with a timestamp later than the local server clock. The data server buffers all the incoming data within the lead time and lag time range, and then publish the data with the same timestamp as a collective measurement frame. The phasor data from all channels are sorted and aligned with the correct timestamps before they are dumped into the historian and transferred to other servers.

B. Data Storage

The capability to write and read large volume of data with high speed is critical for the data historian. After exploring several relational databases, including MS Access and MySQL, and a variety of NoSQL databases including MongoDB and Cassandra, the openHistorian 2.0 developed by GPA is selected as it can best fulfill the requirements.

The openHistorian 2.0 is a file based storage system designed to efficiently integrate and archive SCADA, synchrophasor, digital fault recorder, and other process control data to support real-time grid operations and post-disturbance analysis. It supports indexed data retrieval interfaces and lossless data compression, which largely save the storage capacity of the historian. The archive files produced by the openHistorian are ACID (atomicity, consistency, isolation, and durability)-compliant, representing a very durable and consistent file structure that is resistant to data corruption. Internally the data structure is based on a B+ tree that allows out-of-order data insertion. It also provides high-speed APIs that can be customized for visualization of real-time and historical data, web-based data access, and remote historian data extraction.

C. Application Layer

1) Real-time Applications

The major objective of real-time applications is to detect disturbance instantaneously. All the detection triggers are hosted in the data server, which has fast access to the data as soon as they are parsed and cached into the memory. The disturbance detection triggers are implemented by customizing the Input/Action/Output Interface (IAON) Adapters of the Grid Solutions Framework (GSF), which is the fundamental library collection of openPDC and openHistorian.

The real-time triggers, which extend the action adapter, include event trigger, oscillation trigger, islanding trigger and line trip trigger. The thresholds for these triggers are different for each power grid. With the new infrastructure, these configuration parameters and thresholds are easy to define and modify.

2) Non-real-time Analytics

Non-real-time applications of the FNET/GridEye system mainly include post-event analyzer, data plotting module, and historical data extraction and visualization module etc. All these modules are designed to be modular, so as to easily extend, modify and integrate into the whole system.

Particularly, the data plotting module uses 1) the raw measurement data extracted from the historian on the basis of event time and grid information, and 2) event and oscillation analysis results to generate different types of frequency and phase angle plots. These graphics serve as an intuitive way to present different time periods during power system disturbances, e.g. pre-fault, post-fault, transient period, etc. Combining the information from the analyzers and visualization tools, an event or oscillation report will be generated and then sent out via e-mail automatically.

IV. FNET/GRIDEYE APPLICATIONS

As mentioned above, FNET/GridEye applications can be roughly divided into real-time and non-real-time applications. Real-time applications require response within seconds or even sub-seconds after receiving the measurement data, while non-real-time applications have more flexible timing requirements or are upon request.

A. *Overview of Existing Applications*

In past ten years, a large number real-time and non-real-time applications have been developed based on the FNET/GridEye platform. Some of the important real-time applications include real-time visualization of measurement data (as shown in Fig. 9) [4], disturbance recognition and location [15], [18], [19], inter-area oscillation detection and modal analysis [20], [21], islanding and off-grid detection [22]. The non-real-time applications mainly include event replay and post-event analysis [23], measurement-aided model validation [24], electromechanical speed map development [5], historic data statistical analysis [25]–[27], and forensic recording authentication [28]. Most of these applications have been well documented in previous publications so this section will only briefly describe some of the most important applications.

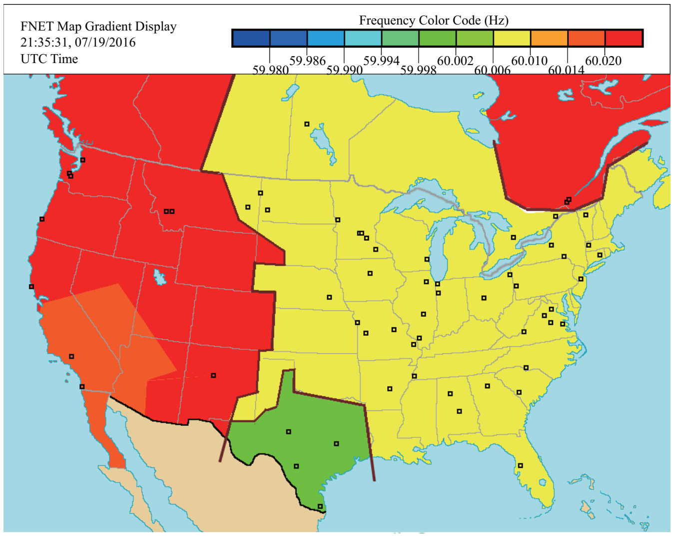


Fig. 9. FNET/GridEye real-time frequency contour map.

The frequency event trigger application detects generator trip and load shedding by continuously monitoring the incoming frequency data. This application uses rate of frequency change ($\mathrm{d}f/\mathrm{d}t$) as an indicator of power system disturbances. If the rate of frequency change exceeds a predefined threshold, disturbance detection will be triggered. A voting mechanism is introduced to avoid false alarms caused by abnormal outliers from some FDR units. After triggering an event, the event analyzer module receives the event time and grid information from the event detection module, reads the corresponding data from the historian and performs the analysis. This application consists of several sub-modules, which include event type classification, event amount estimation, event location estimation, reliability coordinator region identification, and pumped storage unit estimation. Each sub-module is developed independently and compiled as an individual DLL to be called by the event analyzer. With this type of modularization, a sub-module can be easily enabled or disabled for a particular grid. The event location estimation module is based on a geometrical triangulation algorithm making use of the Time Difference of Arrival (TDOA). The estimated location information is passed to report generator module afterwards.

The oscillation detection application utilizes the relative angle. The relative angle deviations are obtained by referencing and normalizing absolute phase angle measurements. The first step of the oscillation triggering is to detect a disturbance by sensing a steep relative angle rise or drop. Once the rise or drop exceeds a threshold, the algorithm will try to identify whether the difference between the maximum and minimum angle value in the next five second is beyond a specific threshold. Further, a voting mechanism is conducted before this oscillation disturbance is confirmed and reported, in order to avoid the false alarms sometimes caused by noisy measurements. Then, the oscillation analyzer receives the time and grid information from the oscillation detection module and extracts near real-time oscillation data from the historian. The analyses that the oscillation analyzer performs include modal analysis, pattern recognition, basic oscillation magnitude calculation, and mode shape analysis. Similar to the event analyzer, all those sub-modules can be easily turned on or off based on the requirements.

The islanding trigger detects the situation in which a part of the grid becomes electrically isolated from the remainder of the power system. The isolated gird is powered by an UPS or backup generation. The trigger uses the absolute difference between a frequency measurement of a certain FDR and the median frequency of all the monitored FDRs within a certain power grid as an indicator of potential islanding cases. Once this difference value is over a threshold, the integration of frequency difference over a certain period of time is calculated and used to compare with another threshold to determine if islanding has occurred. Once a device is confirmed to be islanding, it will be automatically disabled from the oscillation trigger voting process to prevent false-oscillation-triggering.

The line trip trigger de-trends the frequency data using an average frequency filter. Once the trigger detects that the peaks of the de-trended frequency are over certain thresholds, the peak information is further analyzed to see whether these sudden changes can be observed from multiple sensors—a sudden raise on the energy sending side and a sudden drop on the receiving side. If so, the disturbance is identified as a line-trip event.

In the following subsections, a few new applications of FNET/GridEye will be introduced in more details.

B. *Online Estimation of Frequency Initial and Nadir Slopes*

Frequency declines when a power system experiences large, sudden power deficiencies. According to Essential Reliability Service Task Force (ERSTF) Measures Framework Report from North American Electric Reliability Corporation (NERC), using high-speed phasor measurements to track the frequency inertia at the interconnection level is highly desirable. However, it is difficult to achieve that on account of the restricted PMU data accessibility among different utilities.

As shown by Fig. 1, FNET/GridEye has deployed more than 200 units across the U.S. power grids. Different from PMUs owned by different utilities, all the FNET/GridEye sensors send data directly to the data center operated at UTK and ORNL. Therefore, based on the FNET/GridEye platform, the online estimation of inertial and nadir slopes can be achieved.

Since there are sufficient sensors deployed in individual interconnections, and each sensor provides time-synchronized frequency measurements, the median value of the sensors' measurement is recognized as the synchronous frequency value of the interconnection. This online application faces two data quality issues that may impair the estimation accuracy. One is the white noise at the distribution level and the other is the oscillation. Therefore, it is necessary to address these issues before estimating the slopes. Specifically, moving median filter is used to eliminate the white noise. With respect to the oscillations, the high-order polynomial approximation method is capable or removing the oscillations, as shown in Fig. 10.

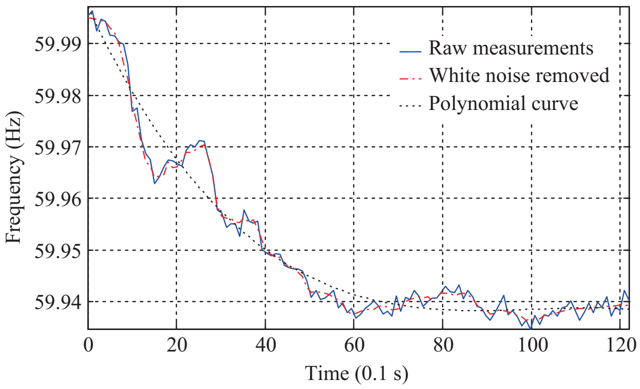


Fig. 10. Frequency measurement data preprocessing.

After the data preprocessing, the initial slope is obtained by calculating the frequency deviation within the first 0.5 second following a disturbance, and the nadir slope is calculated by the slope between pre-disturbance frequency (commonly called point A) and frequency nadir (commonly called point C). These results are embedded in predesigned event reports, as shown in Fig. 11, which contains other important event information, such as the event type and location. Most importantly, system operators will be alerted via an email that includes the event report. This application is being further tested by NERC and its resources subcommittee.

C. Oscillation Detection Using Ambient Measurements

Oscillations are commonly observed in large-scale interconnected power systems and they may threaten system security if they are not sufficiently damped through effective controls. Since the power system operation conditions constantly change, it is important for operators to understand real-time system oscillation characteristics and identify poorly-damped modes. As post-event ring-down oscillations are rare, monitoring oscillation modes in real time can only be based on ambient synchrophasor measurements. Therefore, FNET/GridEye provides an ambient-based real-time oscillation identification function.

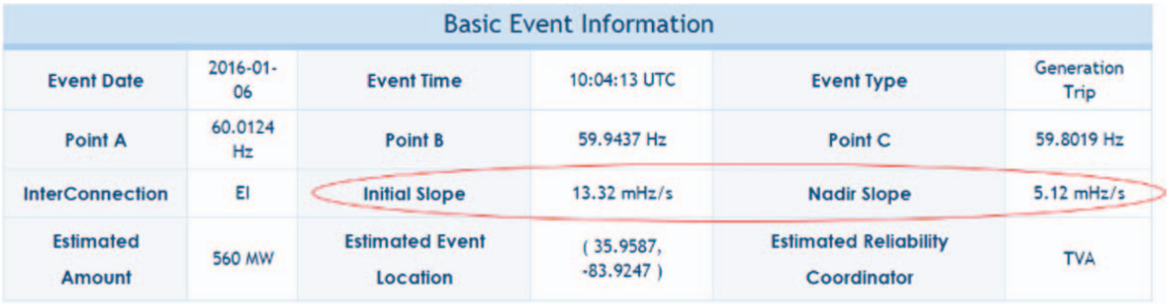
The ambient oscillation mode identification tool is based on Multivariate Empirical Mode Decomposition (MEMD), which is a time-frequency analysis method capable of extracting low-amplitudes synchronous oscillation components in multi-channel measurements [29]. As an example, Fig. 12(a) shows the FNET/GridEye measurements of a selected time window in which a generation trip event happened in the US Eastern Interconnection at 125 s [30]. Fig. 12(b) shows that the oscillation component can be detected in FNET/GridEye using both ambient measurements (before 125 s) and event measurements (after 125 s).

D. Power System Dynamic Response Estimation

Assessing power system dynamics is essential for safe and reliable operation and control of a power system. Synchrophasor provides rich information of system dynamic behaviors in real time. Taking advantage of phasor measurement data, it is feasible to build purely measurement-based models to estimate the dynamic response of system events in order to enhance system dynamic assessment and control. Meanwhile, the measurement-based approach also can circumvent the limitations of circuit-based power system models that lack detailed information. One of FNET/GridEye phasor measurements' innovative applications is to develop data-driven models that can be updated online to estimate [31]–[33], predict [34], or control [35] system responses with high accuracy.

The first step of this application is to select optimal input signals by using the correlation coefficient index (CCI) [36], [37], which is employed to describe the relationship between input and output signals to construct the data-driven model. A commonly used CCI is defined as

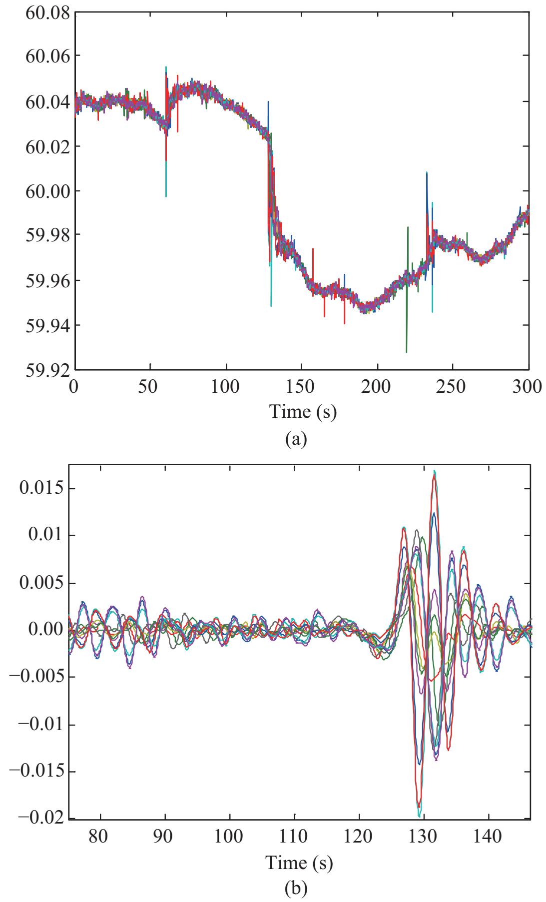
$$r_{ij} = \frac{C(x_i, x_j)}{\sqrt{C(x_i, x_i)C(x_j, x_j)}}$$



Basic Event Information

Event Date	2016-01-06	Event Time	10:04:13 UTC	Event Type	Generation Trip
Point A	60.0124 Hz	Point B	59.9437 Hz	Point C	59.8019 Hz
InterConnection	EI	Initial Slope	13.32 mHz/s	Nadir Slope	5.12 mHz/s
Estimated Amount	560 MW	Estimated Event Location	(35.9587, -83.9247)	Estimated Reliability Coordinator	TVA

Fig. 11. Snapshot of FNET/GridEye event report.



(a)

(b)

Fig. 12. Frequency measurements of a generation trip event happened at 125 s and detected oscillation components in ambient measurements ($<$ 125 s) and event measurements ($>$ 125 s). (a) Frequency measurement. (b) Oscillation components.

where i and j are the input and output signal index, respectively, and C is the covariance function. Fig. 13 exhibits the CCIs for voltage angle measurements of the FDRs deployed in the U.S. Eastern Interconnection. Based on the CCI analysis, the optimal input locations for a certain output location can be determined.

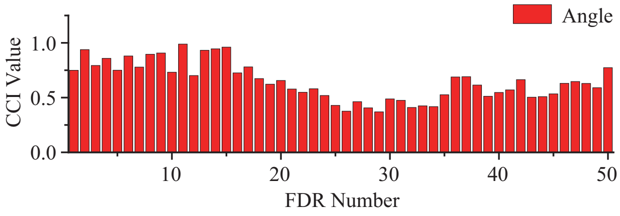


Fig. 13. Angle correlation and frequency coefficients index.

The benefit of the input signal selection is that the number of model inputs can be reduced for the sake of higher model updating rate and better model accuracy. Once the input and output signals are determined, one set of data is needed to train the model and another set of data will be applied to estimate the dynamic response and evaluate the results, one example of which is given in Fig. 14.

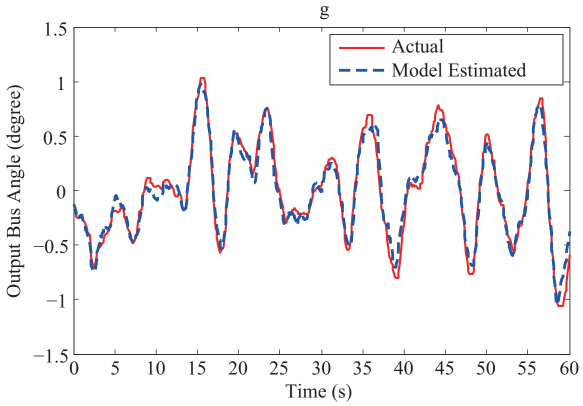


Fig. 14. Dynamic response estimation results.

V. CONCLUSION

Global implementation of PMU-based WAMS is strongly limited by its high expenditure and wide deployment between utilities. As a pilot WAMS deployed at the distribution level, FNET/GridEye is specifically applied to system dynamics monitoring. It is considered as a perfect complement of WAMS and proves to be an effective situational awareness tool for electric utilities, independent system operators, and regulatory agencies. FNET/GridEye is growing with achievements on groundbreaking research, high-end techniques, and low-cost maintenance compared with PMUs. Taking advantage of the highly accurate GPS-synchronized phasor measurement, amount of real-time and non-real-time applications have been developed and implemented on this system. Many of these applications can be integrated into existing electric utility control centers to enhance situational awareness capabilities for power grid operators.

FNET/GridEye will continue to explore valuable applications in power system dynamic monitoring and pioneer the development of wide-area monitoring system in power systems. As the global energy interconnection is becoming a research focus, FNET/GridEye can serve as an ideal platform for global-scale interconnected grid situation awareness.

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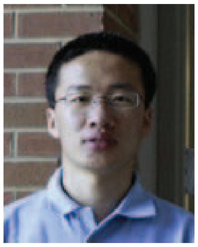

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