FNET/GridEye: A Tool for Situational Awareness of Large Power Interconnetion Grids

Lin Zhu[1], Shutang You[1], He Yin[1], Yinfeng Zhao[1], Fuhua Li[1], Wenxuan Yao[2], Chris O'Reilley[2]
1. Dept. of Electrical Engineering and Computer Science
The University of Tennessee, Knoxville
Knoxville, TN, USA
Email: lzhu12@utk.edu

Wenpeng Yu[1], Chunjie Zeng[1], Xianda Deng[1], Yi Zhao[1], Yi Cui[1], Yao Zhang[1], Yilu Liu[1,2]
2. Division of Energy and Transportation Sciences
Oak Ridge National Laboratory
Oak Ridge, TN, USA
Email: liu@utk.edu

Abstract - **This paper gives an overview of a wide-area measurement system deployed at the distribution level: FNET/GridEye, which consists of hundreds of sensors, communication and a data center. The sensors are utilized to take frequency, voltage phase angle and magnitude measurements from the ordinary 110 or 220V outlets in offices or residential houses. These measurements are continuously transmitted to the data center via Internet. Many applications have been implemented to monitor large-scale interconnected power grids, and interpret grid operation status to improve system operators' situational awareness capability. Some representative online and offline applications are presented in this paper, as well as several recently developed new applications.**

Index Terms - **Data analytics, power grid, situational awareness, PMU.**

I. Introduction

Power grids are probably the largest and most complicated manmade systems, which could transcend multiple countries and even the entire continent to convey electric power to consumers. Therefore, wide-area situational awareness technologies to monitor power grids is essential for system reliability. With the development of synchrophasor technology in 1980's, the Phasor Measurement Unit (PMU) based Wide-area Measurement System (WAMS) has the ability to reveal important real-time insights of the power grid dynamics, GPS-synchronized, high resolution, and high-precision measurements [1], [2]. Nevertheless, installing many PMUs is expensive and limits the deployment of PMUs and WAMS in power industry.

Unlike other WAMSs, e.g., GE's PhasorPoint, that are deployed in the transmission system [3], [4], FNET/GridEye is deployed at the distribution level. FNET/GridEye consists of hundreds of quickly deployable and GPS-synchronized sensors, communication and a data center [5], [6]. The sensor measures the GPS-synchronized frequency, phasor angle, and voltage magnitude [7], [8]. These synchronized measurements are sent to data servers of FNET/GridEye through Internet to perform monitoring and advanced situational awareness applications. FNET/GridEye can easily implement and test new and advanced WAMS applications to significantly improve the maturity level of phase measurement technologies.

FNET/GridEye is maintained by the University of Tennessee at Knoxville (UTK) and Oak Ridge National Laboratory (ORNL). It covers all five major North American power grid interconnections. Many applications have been developed for real-time alerts of major grid events and oscillations to subscribers [9]. By 2020, FNET/GridEye has supported secure and stable operation of U.S. power grids for 16 years. This paper presents the overall architecture and representative online/offline applications of FNET/GridEye.

II. FNET/GridEye Architecture

The overall architecture of system is given in Fig. 1. It includes three levels: sensor/measurement level, communication level, and data center level.

A. Sensor/Measurement Level

FNET/GridEye sensor, called Frequency Disturbance Recorder (FDR), is a quickly deployable and low-cost synchrophasor measurement device at the distribution level. It takes synchrophasor measurement at ordinary 110V or 220V outlet on a wall. Fig. 2 shows an UGA, which has only three interfaces: power, GPS antenna and network. UGA is the newer version of FNET/GridEye sensor, on which several new functions have been implemented, including harmonic measurements (2nd-15th order), signal-noise ratio, and voltage abnormity detection. In order to capture accurate frequency, angle and harmonic, the reporting rate of the UGA is required to be as high as possible. As one of the criteria listed in IEEE C37.118, the reporting rate of the PMUs are ranged from 10 FPS to 60 frames/second. In addition, in the newest standard, i.e., IEEE P60255-115-1 draft, the highest reporting rate increases from 60 frames/second to 120 frames/second [10]. Therefore, the synchrophasor data reporting rate is increased to 120 frames/second to meet the new requirement. The detailed comparison of FDR and UGA is given in Table I.

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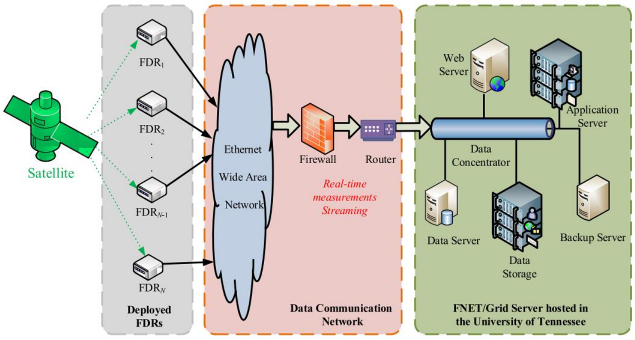
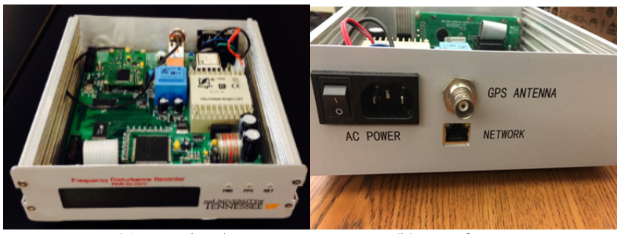


Figure 1. FNET/GridEye achitecture.



(a)UGA hardware (b) Interfaces

Figure 2. FNET/GridEye sensor: UGA.

TABLE I. COMPARISON OF FDR AND UGA

	FDR	UGA
Measurements	Frequency, voltage mag., voltage angle	Frequency, voltage mag., voltage angle
Harmonic	N/A	Yes, 2nd-15th order
Signal-noise ratio	N/A	Yes
Voltage sag	N/A	Yes
Reporting rate	10 frames/second	120 frames/second
Communication	Private protocol	IEEE C37.118
Data compression	N/A	Yes

Up to now, around 200 FDRs/UGAs are taking measurements in North American power grids, while more than 70 FDRs/UGAs are measuring power grids in other countries [11]. The FDRs/UGAs deployment locations are given in Fig. 3 and Fig. 4.

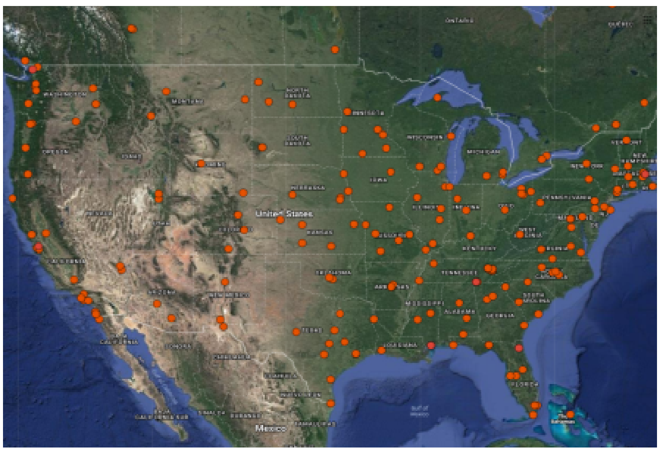


Figure 3. FDR/UGA deployed in North America.

Figure 4. FDR/UGA deployed around the world.

B. *Communication Level*

FDRs utilize a private communication protocol for their communication with data center. Recently, the standard communication protocol IEEE C37.118 is implemented on UGAs to transport the synchrophasor measurements [12]. Since UGAs are deployed at the distribution system with limited communication bandwidth. Data compression technologies have been developed to compress UGA measurement data. Multiple measurements can be compressed into one data frame. As shown in Fig. 5, thanks to the data compression algorithm, the streaming measurements with high reporting rate (120 frame/second) only take limited network bandwidth. The synchrophasor measurements are finally sent to the servers via Internet.

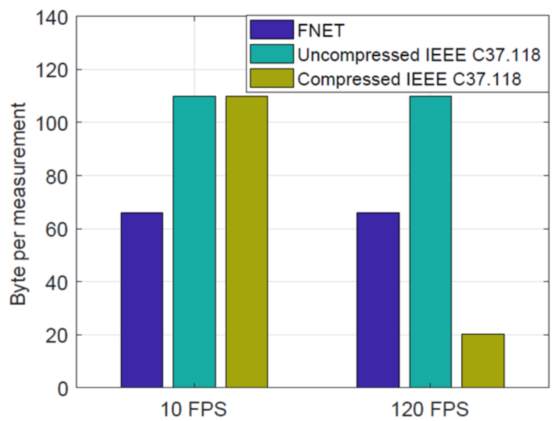


Figure 5. Data packet compression.

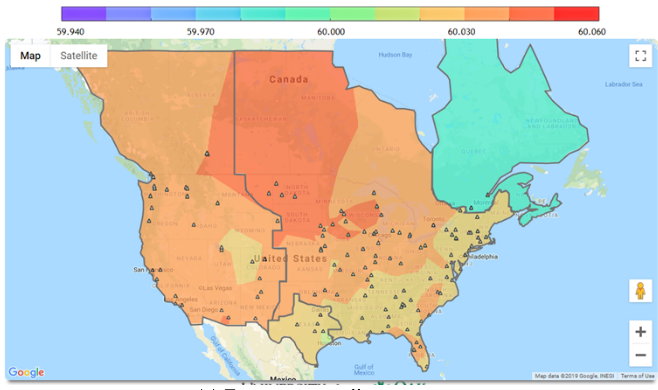
C. *Data Center Levle*

The data center level includes the servers to process real-time data, run real-time applications and offline analysis. The data center is physically located in UTK and ORNL. The data quality from FDRs are monitored and visualized in real-time. The data processing server has a backup server to avoid data loss during server failures. The real-time applications server includes multiple functions, such as visualization, oscillation monitoring, event locating, and real-time email alert on grid events. The servers can intake and process a large amount of streaming data, and build high-level applications to improve system situational awareness.

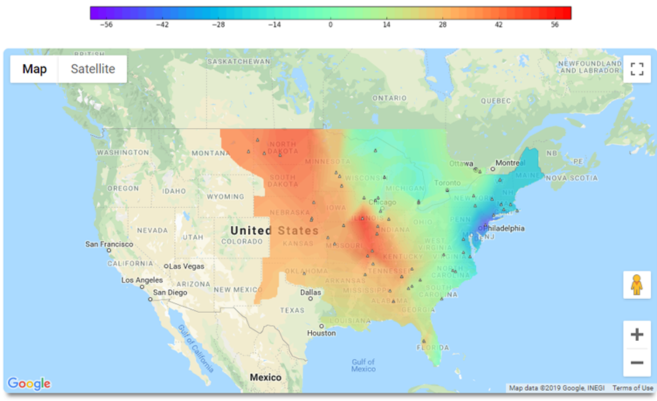
III. Overview of Existing Applications

A. *Real-time Visualization*

System operators rely on real-time measurements for power system situational awareness. The real-time visualization application can intuitively display frequency and angle measurements in both space dimension and time dimension [11]. Fig. 6 shows the snapshots of the frequency gradient map and the angle contour map, which could provide a whole picture of power grid to system operators. Note that the angle contour map visualizes the real-time angle "differences" with respect to a referential point in U.S. Eastern Interconnection.



(a) Frequency gradient map



(b) Angle contour map

Figure 6. Real-time visualization.

B. *Online Event Detection, Location and Alert*

Being aware of disturbances and events in time is very important for system operators to monitor and control large-scale power grids. When a significant disturbance/event occurs, such as trip of generators, loads, and transmission lines, the frequency and angle vary with respect to time and space. The online event detection, location and alert application can capture the disturbance/event, and estimate the location and size of the disturbance/event using the time delay of arrival (TDOA) approach and the beta value based method [13], [14]. The event alerts are sent out through emails in real-time, with event type, location and estimated power mismatch amount. Fig. 7 shows a load shedding event captured by FNET/GridEye in 2011. An estimated 610MW load shedding event happened in U.S. Western Interconnection is detected by this application.

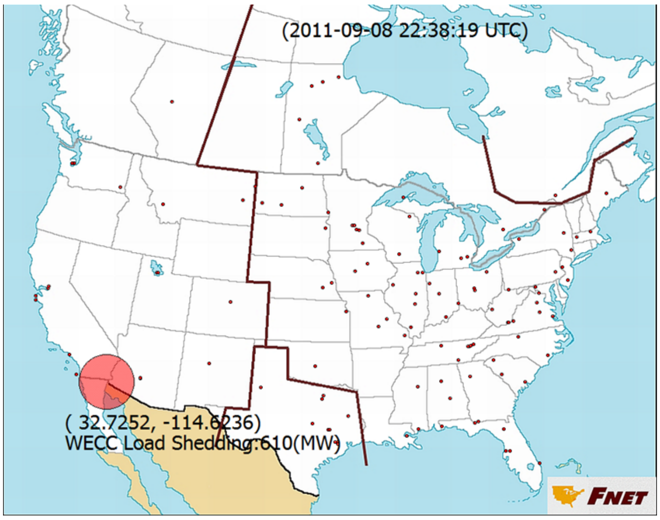
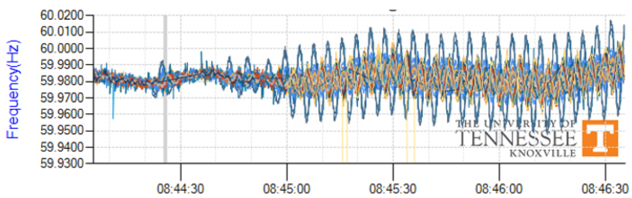


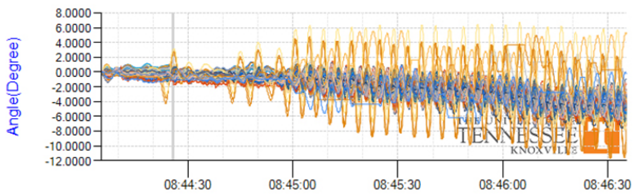
Figure 7. Event location: Southeast Blackout 09/08/2011.

C. *Real-time Oscillation Detection and Alert*

Inter-area oscillation limits the transmission capability and potentially compromises system security. By utilizing the real-time measurements, either frequency or phasor angle, the low-frequency oscillations can be detected quickly because of their specific signature. The online low-frequency oscillation detection and alert application analyzes the real-time measurements collected by FNET/GridEye. After the detection of an oscillation, an alert is sent to the subscribed clients and automatically archives the measurements prior to and after the event. This application can detect both natural oscillations and forced oscillations. Fig. 8 shows the detected forced oscillation which is observed across the entire U.S. Eastern Interconnection in January 2019 [15]. Both frequency and phase angle measurements indicate that this is a sustained oscillation with 0.25Hz oscillation frequency.



(a) Frequency



(b) Phase angle

Figure 8. Detected forced oscillation in EI 2019.

D. *Event Playback and Analysis*

Large-area blackouts will result in tremendous economic loss. FNET/GridEye measurements during a blackout can be used to reconstruct the event scenario for post-event analysis. For instance, as shown in Fig. 9, measurements were used to replay the 2011 hurricane Sandy event in northeast U.S. [11] This application helps post-event analysis activities and aids in the development of tools to improve system resiliency.

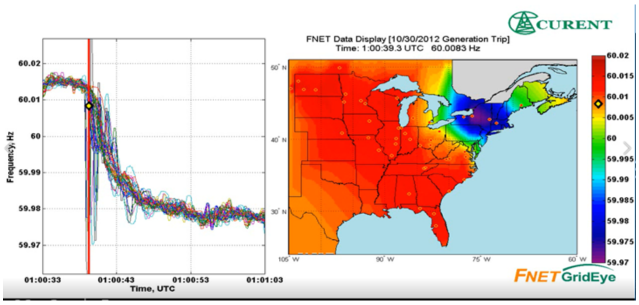


Figure 9. Event playback: 2011 Hurricane Sandy Event.

E. Model Validation

System dynamic models are often inaccurate due to the complexity and uncertainties in a huge number of components. Some applications designed based on this inaccurate model may not perform as well as expected. Therefore, model validation is an important function highly desirable by utilities to improve the accuracy of their planning models. Using FNET/GridEye synchrophasor measurements, the dynamic model can be validated and tuned to make its response better match the realistic system response [16]. As shown in Fig. 10, after tuning inertia time constant and governor parameters using measurements from FNET/GridEye, the simulated frequency response of the planning model is much closer to the realistic frequency measurements. This would be a good example to demonstrate how the FNET/GridEye measurements are utilized for model validation.

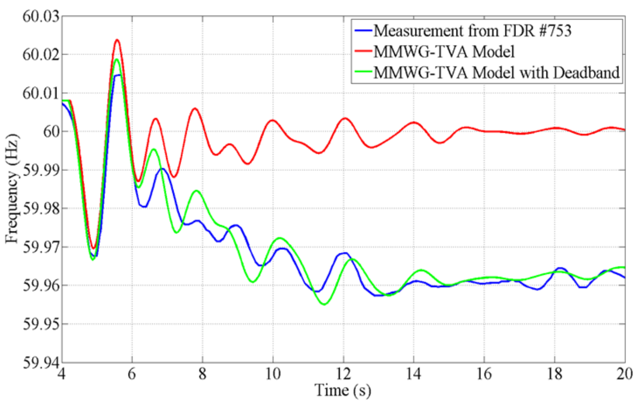


Figure 10. Model validation using FDR synchrophasor measurements.

Due to page limitation, other online and offline applications including islanding detection and alert, fault-induced delayed voltage recovery (FIDVR) detection, islanding detection/alert, historical data statistical analysis, and digital audio authentication, etc., are not introduced in this paper. Please refer to [11] and [17] for more details.

IV. Selected New Applications

A. Online Ambient Oscillation Mode Minitor

Considering the constantly variations of operating condition, continuous oscillation modal information is highly desirable so that appropriate measures can be taken in real-time to prevent any serious inter-area oscillations. To that end, the online ambient-data-based oscillation modal analysis is developed [18]. This oscillation modal analysis method no longer needs to rely on disturbance data and thus can assess power grid stability continuously. As shown in Fig. 11, the oscillation frequencies and damping ratios of two dominant modes in U.S. Western Interconnection are estimated using this new online application.

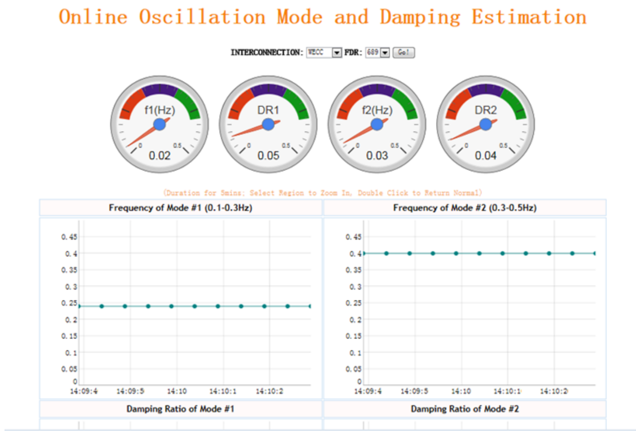


Figure 11. Online oscillation mode analysis using ambient measurements.

B. Advanced Data Analytics

To better estimate the disturbance location and power mismatch after a disturbance, the machine learning technology is employed. Relevant FDRs are selected using Recurrence Quantification Analysis (RQA) [19], and critical features are extracted using Minimum Volume Enclosing Ellipsoid (MVEE) [20]. In conjunction with advanced Multivariate Random Forest (MRFR) algorithm [21], the new approach using machine learning provides a better accuracy in estimating the disturbance location and power mismatch, compared with previous method based on beta value. Fig. 12 shows an example, in which the estimated disturbance location is very close to the confirmed location. As shown in TABLE II, the accuracy of mismatch estimation is much higher than the conventional Beta value based method.

TABLE II. Mismatch Estimation Comparison

Mismatch estimation error	Beta value based method	RQA-MVEE method
<10	45%	80%
<20	70%	95%
<30	95%	100%

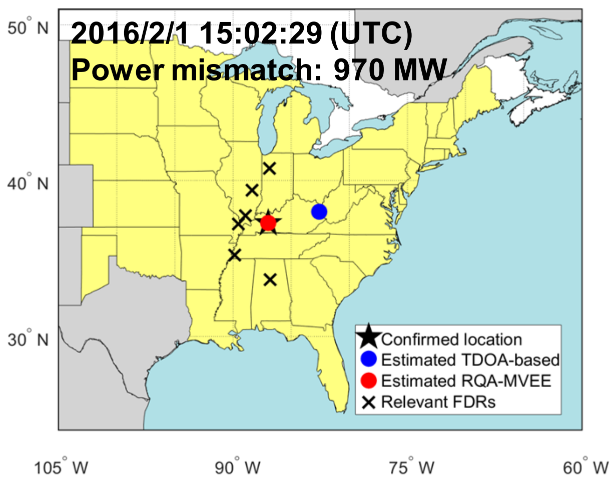


Figure 12. Comparison of the estimated disturbance location.

C. Measurement-driven Damping Control Design

Most oscillation damping controllers are developed based on system dynamic models and have pre-determined parameters. However, the system dynamics is constantly changing, which often cannot be represented by the dynamic models used for controller design and parameter setting. Based on FNET/GridEye and ancillary PMU measurements, measurement-based damping control can be developed to help controller adapt to changing system conditions. The control effect of the measurement driven damping controller is shown in Fig. 13. The case without controller represents an event happened in the Italy power grid in December 2017. The measurement-driven controller is shown to able to damp the oscillation effectively. The case with two measurement-driven controllers has even better oscillation damping performance than the cases with only one controller [22].

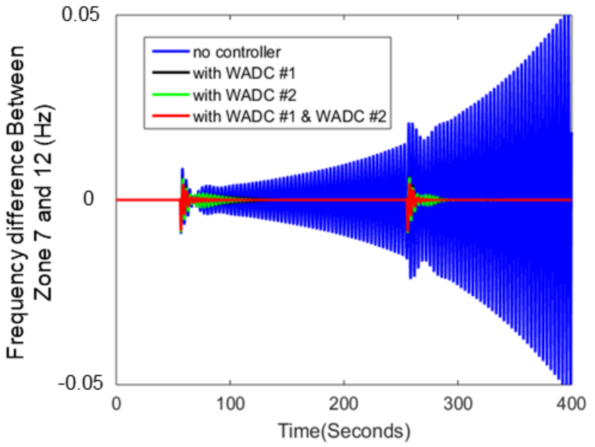


Figure 13. Control effect of oscillation damping controllers using measurement-driven model.

V. Conclusions

Due to its low-cost and quickly deployable features, FNET/GridEye is a good platform to further explore the full potential of phase measurement technologies for both academia and industry. FNET/GridEye will continue to develop more WAMS-enabled applications by leveraging machine learning technology and big data solution to facilitate the field implementation of measurement-based applications.

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