A Time-synchronized Power Grid Monitoring System at the Distribution Level

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Abstract

In order for further observation of the power system, wide-area monitoring systems (WAMS) have been extended from the transmission to distribution level in the past few years. As a pioneering WAMS deployed at the distribution level, the frequency monitoring network FNET/GridEye has been providing independent observation of U.S. and other worldwide power grids dynamic performance continuously since 2004. By utilizing GPS-time-synchronized monitors called frequency disturbance recorders (FDRs), FNET/GridEye is capable to capture dynamic grid behaviors (e.g., frequency and voltage phase angle). Compared to the three-phase phasor measurement units (PMUs), the FDRs can be conveniently deployed across the grid at distribution level without complex procedure and heavy outlay. With years' continuous development and systematic management, FNET/GridEye has thrived with multiple advanced real-time and non-real-time applications. The system has been proved to be highly effective in enhancing power grid operators' situational awareness capabilities. In this paper, the latest accomplishments of FNET/GridEye data analytics applications will be introduced.

1. Introduction

With dramatically increasing penetration of renewable energy generation in power system, the system operators are facing various unprecedented challenges. One of them is the fast and stochastic change caused by renewable resources, which cannot be effectively captured by the traditional Supervisory Control and Data Acquisition (SCADA) system. The promising solution so far is the deployment of phasor measurement units (PMUs), which is a blooming situational awareness tool capable of providing GPS-time-synchronized measurements of grid status with high time-resolution **Error! Reference source not found.**. It reveals more detailed insights into worldwide systems dynamics [2], even with the presence of renewable generations [2]. However, extensive deployment of PMUs are impeded considering the associated high manufacturing and installation costs.

Originally developed in 2003, the frequency monitoring network FNET/GridEye is a unique wide-area phasor measurement system deployed at the distribution level [4]-[7][7]. It collects system status data (frequency, voltage magnitude, voltage phase angle, as well as power quality information) using low-cost, high-accuracy, GPS-synchronized frequency disturbance recorders (FDRs), which can be roughly considered as a single-phase PMU device. It takes inputs from single-phase 120-V electrical outlets and therefore successfully bypasses the complex installation procedure. As a complete wide-area monitoring system, all the FDRs' phasor measurements are collected by the FNET/GridEye server hosted at the University of Tennessee, Knoxville (UTK), and Oak Ridge National Laboratory (ORNL) for technical management and cutting-edge researches. A large number of applications have been developed to help the system operators interpret the power grid operation status and take proactive actions to prevent blackouts.

Compared to recent counterparts, FNET/GridEye is way ahead in several aspects: Firstly, its customer-side design promotes its plug-and-play feature and minimizes the manufacture cost and installation effort. Secondly, it achieves higher measurement accuracy than counterparts. For instance, the Micro-PMU's angle accuracy is expected to be within ±0.05° [8] while FNET/GridEye has already achieved ±0.005°. At the end, the most importantly, FNET/GridEye has successfully developed and implemented a series of data visualization and analytics applications. It is widely welcomed by the academia, industry as well as government. Fig.1. shows the current FDR installation locations in North America.

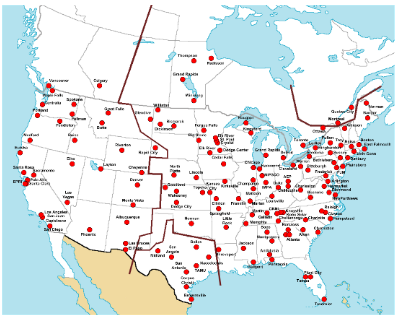


Fig. 1. Map of FDR locations in North America

This paper introduces the prominent achievements enabled by FNET/GridEye. It is structured as follows: After a brief introduction of the overall framework of FNET/GridEye in Section 2, several significant real-time applications of FNET/GridEye are presented in Section 3; Section 4 depicts the various non-real-time data analytics functions; and Section 5 concludes the paper.

2. FNET/GridEye Framework

FNET/GridEye system consists of two major parts: sensors that scattered all over the power grid and data server hosted by UTK and ORNL [9][6]. FDR is an embedded microprocessor system with GPS time synchronization and Ethernet communications capability [10]. For now, three generations of FDRs have been developed to consistently pursue for higher measurement accuracy and better data quality. The most-deployed Generation-II FDR is shown in Fig. 2. A series of hardware and firmware updates have been added in order to further enhance the devices' performance and extend their applications for the Gen-III FDRs [11] [12]. For example, the steady-state phase angle and frequency measurement error of the Gen-III FDRs is less than 0.003° for angle and 0.00006 Hz for frequency, compared with 0.01° and 0.0005 Hz for Generation-II.

Fig. 2. Photo of Generation-II FDR

The other part of FNET/GridEye is the data center, where the measurements provided by FDRs are systematically managed, technically processed, and safely archived. The data center can be treated as a multi-layer data management system as shown in Fig. 3. The first and most important component is the data concentrator, where real-time measurements are extracted from the network TCP/IP data package, interpreted, error checked, time-aligned, and then streamed into different layers for application or storage. The second layer of a data center hierarchy is composed of the real-time application agent and the data storage agent. The real-time application agent consists of various real-time application modules (e.g., disturbance detection and oscillation detection).

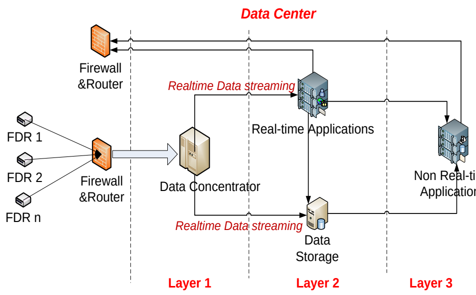


Fig. 3. FNET/GridEye data center structure

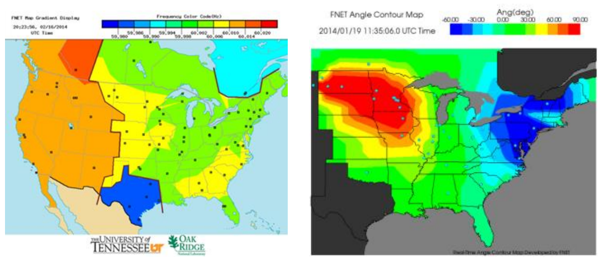
The third layer of data center is the non-real-time application agent. Applications implemented on this layer are operated on various saved data formats instead of real-time streaming data. This multi-layer data management system successfully deals with the various time requirements of different functionalities and accomplishes the efficient collection, storage, and utilization of real-time data. In the following two sections, various real-time and non-real-time applications run on the data center will be introduced respectively.

3. Real-time Applications

The most valuable feature of FNET/GridEye is providing real-time information of the power grid operation. With plenty of FDRs deployed across the U.S., the FNET/GridEye measurement is able to describe the behaviors of the national-level power grids as a whole, instead of limited information from certain utilities hosting PMUs in their isolated territories. A large number of applications have been developed, which can be divided into real-time and non-real-time roughly by their response time frame. Real-time applications require fast response within seconds or even sub-seconds after receiving the measurement data, while non-real-time applications have more flexible timing requirements[13]. In this section, some of the significant real-time applications and related researches are presented.

3.1. Real-time Visualization of Measurement Data

Real-time visualization of wide-area measurement data is one of the FNET/GridEye system's most important applications. Correlating streaming wide-area frequency and voltage angle measurements with corresponding FDRs geographical location information, the FNET/GridEye system creates an intuitive real-time visualization tool that helps operators better interpret the power grids operation status in real-time [1][14]. Compared with PMUs hosted by certain electric utility, FNET/GridEye provides a full coverage and thus presents a whole picture of the entire North American power system. Fig. 4 shows a snapshot of the real-time frequency and angle contour map of the North American power system respectively. These maps can be accessed through the FNET/GridEye web services.



a. frequency contour map b. voltage angle contour map

Fig. 4. FNET/GridEye real-time visualization

3.2. Disturbance Recognition and Location

Disturbances like loss of a generator or tie-line cause blackouts. Some of them may result in enormous economic losses. In order to minimize the damage and avoid cascading power outage, it is necessary to recognize and locate the disturbances in time. Continuously receiving the streaming frequency measurements from multiple locations in the grid, FNET/GridEye has achieved automatic disturbance recognition and location function. As an indicator of power system disturbance, if the rate of change of frequency df/dt exceeds a pre-defined threshold, the disturbance detection module will be triggered. For a particular power grid, the threshold is tuned by both practical field tests and real measurement in FNET/GridEye. Based on its frequency response characteristics, the disturbance can be categorized to be generation trip, load shedding, and line trip, etc. Then a geometrical tri-angulation algorithm making use of the time difference of arrival (TDOA) will be utilized to locate this disturbance [15]. An informative FNET/GridEye event report (as shown in Fig. 5) will be generated and sent out automatically to service subscribers, such as utility operators, in seconds. The report provides estimations of critical indices of the disturbance, such as event time, location, type, the frequency value at ABC points, as well as a frequency plot. There are tailored disturbance recognition and location applications running in FNET/GridEye application server for different power girds.

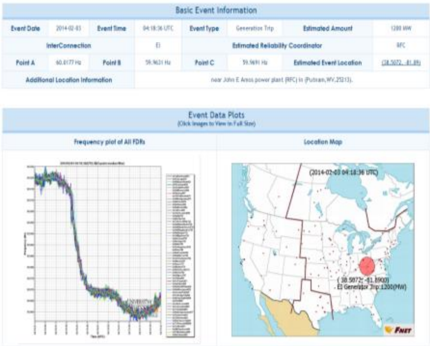


Fig. 5. FNET/GridEye disturbance recognition and location report

3.3. Inter-area Oscillation Detection and Modal Analysis

Small-signal stability is a key concern of power system operators, which could lead to widespread blackouts. The capability of monitoring power grid dynamics in real-time offers the FNET/GridEye sufficient resources to explore rational tools to detect and analyze the inter-area oscillations. Utilizing a frequency or angle-based oscillation detection algorithm, FNET/GridEye has been running effectively in detecting the low-frequency inter-area oscillations [16]. Employing a multi-channel matrix pencil algorithm, a modal analysis of each oscillation event can also be performed. Once an oscillation is detected, involved FDRs can be clustered based on the frequency and relative angle showing the oscillated generators geographically (an example shown in Fig. 6). The FDR observing the largest oscillation amplitude will be provided to narrow the fault location. The frequency and damping ratio information of dominant modes will also be computed and given. The associated inter-area oscillation analysis information will be included in an oscillation analysis report and sent to service subscribers in seconds.

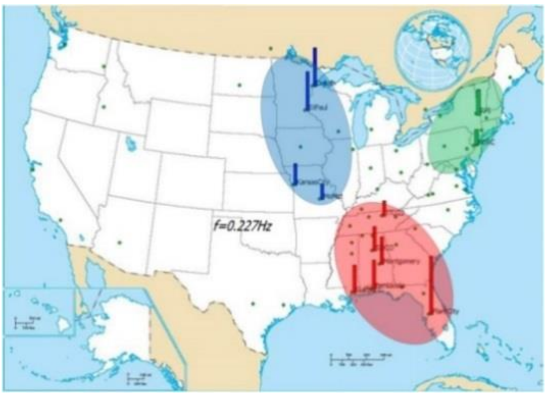


Fig. 6. FNET/GridEye oscillation mode shape map

3.4. Ambient Data-based Oscillation Mode Frequency and Damping Ratio Estimation

The estimation of oscillation modes is critical to the monitoring and damping of low frequency oscillation in power system. The ambient data is a natural response of power system due to the small-magnitude stochastic disturbances, random load switching, etc. The FNET/GridEye ambient data-based oscillation analysis application identifies the low frequency oscillation properties despite the embedded higher noise. The application module employs an empirical mode decomposition (EMD) filter [17] to de-trend the ambient signal, and then utilizes an auto-regressing moving-average (ARMA) model to abstract the oscillation mode frequency and damping ratio information [18]. Most strikingly, by use of an innovative multi-channel parallel processing design, the function module has the capability to process hundreds of streaming FDR measurements at the same time, which gives a whole picture of the entire North American power grids oscillation information in real-time for the first time ever. Fig. 7 shows the oscillation mode frequency and damping ratio calculation results of a single FDR.

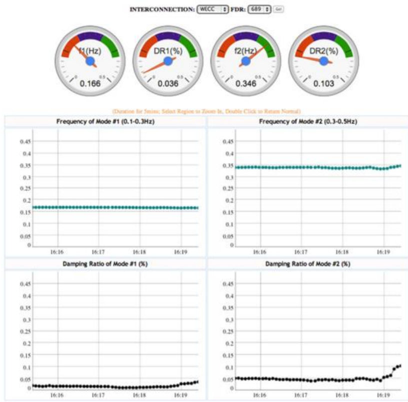


Fig. 7. Online oscillation mode frequency and damping ratio display

3.5. Islanding and Off-grid Detection

Islanding is an extremely dangerous phenomenon in power grids that occurs when one or more generators are no longer working synchronously with the rest of the power system. It could cause serious equipment damages. However, this scenario would become more and more common as the penetration of renewable energy sources keeps increasing. The FNET/GridEye islanding detection module takes advantages of the global observation of system dynamics and triggers an islanding event when the integration of frequency difference between some FDRs and the system average is over a certain threshold. Fig. 8 shows a typical islanding event detected by this module. It is obvious all FDRs are connected with the same grid originally. The subsystem where the involved FDR is connected (as represented by purple curve) was separated from the main grid and then reconnected after about one minute. Similar to other real-time applications, a notification will be sent to related grid operators once one or more FDRs detect abnormally large frequency differences within seconds, which indicates certain sub-systems (or generators) have become islanded from the others[19].

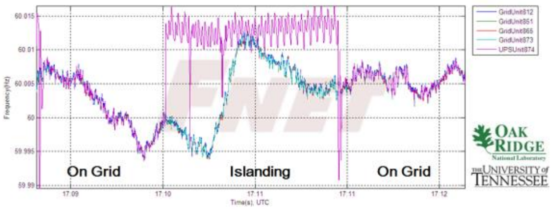


Fig. 8. Islanding event detected by FNET/GridEye

4. Non-real-time Applications

The real-time applications rely on the timely communication of streaming measurement from FDRs. Besides those real-time applications, FNET/GridEye also has developed a series of non-real-time data analytics applications exploring the potentials of the archived data. Some of them are briefly introduced in this section.

4.1. Measurement-aided Model Validation

As one of the most important non-real-time applications, FNET/GridEye frequency measurement have been efficiently utilized to validate the dynamic model of U.S. power grids. The Eastern Interconnection (EI) multi-regional modeling working group (MMWG) is responsible for developing EI power flow and dynamic base case models for further augment the system reliability. These models have to be proved capable to reproduce system operation and frequency response in reality. As a pragmatic and feasible approach, this measurement-aided model validation application can tell whether the model is accurate enough to give a creditable frequency response by comparing the real frequency response recorded by FNET/GridEye to the dynamic simulation results. This potent application has successfully verified system models for several grids. Plenty of valuable validation experience is obtained for fast and efficient validation for future models. Fig. 9 shows the comparison result of model responses before and after validation based on FNET/GridEye measurement. It is obvious the frequency response simulation accuracy was significantly improved [20] after validation. This example reveals the great potential of FNET/GridEye measurement in large-scale power system model validation.

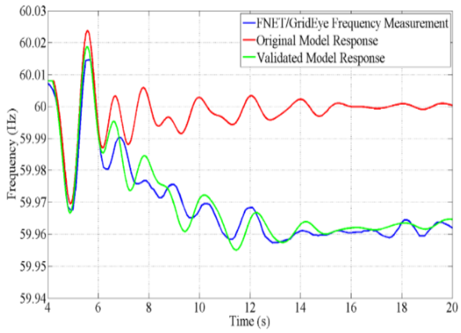


Fig. 9. FNET/GridEye frequency measurement model validation

4.2. Event Replay and Post-event Analysis

FNET/GridEye observes the grids from a comprehensive perspective on account of the deployment of FDRs in large area, which makes it stand out from other WAMSs. Every disturbance leaves a trace in FNET/GridEye. These footprints are used to replay the events. For instance, the shocking Florida blackout in 2008, which led to the loss of 22 transmission lines, 4,300 MW of generation was reconstructed with the help of FNET/GridEye record as shown in Fig. 10. It can be clearly noticed that this event originated from the Florida area, then propagated to the entire Eastern Interconnection (EI). Event replay based on realistic measurement facilitates the post-event analysis and effectively helps avoid similar blackouts in the future. Currently this application has been improved to be able to automatically upload replay movies of severe events to Youtube for public review. It can be seen at the following channel: http://www.youtube.com/channel/UC40n2KTjwRhC9_CvtIasaWA.

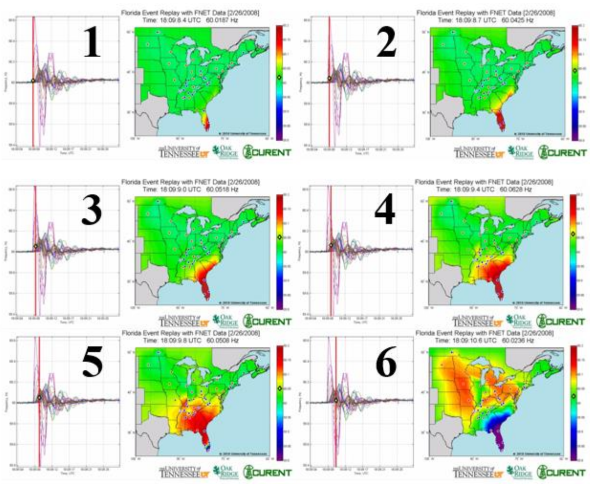


Fig. 10. Florida blackout replay by FNET/GridEye

4.3. Historic Data Statistical Analysis

FNET/GridEye system has been online for several years since its debut in 2004. Along with its own growth, large amount of data has been collected from scattered deployed FDRs, which makes FNET/GridEye extremely informative. A serial of statistical analysis applications have been developed utilizing FNET/GridEye historic data to disclose various system operation characteristics. For instance, years' of frequency response records of disturbances happened in North America are analyzed employing certain data analytics techniques. It achieves to describe the change of system inertia in large grids, which is known to be invisible under normal operation. Additionally, the impact of social events that involve a large population like the FIFA World Cup or the NFL SuperBowl on the power grids has been continuously analyzed [21]. It is discovered that significant frequency swings happened at commercial intervals and half time show frequently, which demonstrates that large-area synchronized social activities would challenge the system operation at certain moment. Considering the increasing penetration of renewable energy source, statistical analysis applications would further benefit the power grid operators by observing the influence of distributed generation, predicting system behaviors, and maintaining system reliability.

4.4. Other Applications

Plenty of other applications performing on FMET/GridEye have also provided unique insights of the power grid. For instance, the development of data-driven models has overcome the incompletion and inaccuracy of circuit-based power system model [22] [23][22] ; the estimation of electromechanical wave propagation speed based on FNET/GridEye measurement has opened a new solution for understanding its different propagation speeds across the entire grid [24]; and the continuous time-marked frequency measurements from FNET/GridEye can also be used as criterion to authenticate suspect digital sound or video recording [25].

5. 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 researches, 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.

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