FNETVision: A WAMS Big Data Knowledge Discovery System

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***Abstract*—With the continuous growing of the power grid, wide area measurement system (WAMS) has been studied and deployed widely. In WAMS, a phasor data concentrator (PDC) collects and persists the GPS-time-synchronized phasor data from hundreds of phasor measurement units (PMU). Due to the size and complexity of the modern power systems, the number of deployed PMUs has been increasing and their data size becomes increasingly large. The large data volume challenges the analysis, and the knowledge discovery of the measurement data. This paper takes the pioneering distribution level WAMS- the frequency monitoring network FNET/GridEye as an example. It develops an adaptive visualization system- FNETVision to visualize the large-volume WAMS data by interconnection. The case studies suggest, based on the FNETVision system, the system administrator can quickly dig out issues of the FNET system and accordingly pinpoint the cause of these issues.**

***Index Terms*—Frequency Disturbance Recorder (FDR), Big Data, Knowledge Discovery, Frequency Monitoring Network (FNET), Visualization**

I. Introduction

As wide-area monitoring systems (WAMS) keep growing to monitor large interconnected power systems, the number of Phasor Measurement Units (PMUs) is also growing rapidly. Take a typical PMU, the Frequency Disturbance Recorder (FDR) as an example, since the initiation of the Frequency Monitoring Network (FNET), the number of FDRs installed across the world has increased from 12 in 2005 [1] to 512 till August 2017. In the FNET system, 156 FDRs are streaming data to the PDCs in the FNET data center located in the University of Tennessee, Knoxville. The fast increase in the number of FDRs and stringent criteria for system integrity violation are believed to result in fold expansion in the already large volume of FDR data. In the FNET system, 150 FDRs streaming 10 measurements at 10 Hz rate generate over 10 GB data per day. Higher streaming rate of 30 Hz, 60 Hz, and 120 Hz in modern WAMS will increase this data volume to 30 GB, 60 GB, and 120 GB respectively. The PDCs within the FNET system receive, store, and analyze this large volume data. Fig. 1 shows the locations of the FDRs in North America.

Clearly, this large volume data lays some performance challenges for the data analysis across the FNET system. (1) Given all the active FDRs are streaming data at 10Hz rate, a PDC will deal with at least 1000 records per seconds. If the analytical programs are also running on this PDC, the usage of the computational resources can be critical. (2) While the present dedicated visualizations [12, 13, 14] can detect power system issues, such are power system disturbances, they cannot easily detect device issues (e.g. data quality). Take the islanding analysis for an example. If an FDR unit is placed in USA, but it is in fact connected to the Hydro Quebec (QUEBEC) interconnection [2], it will constantly trigger the islanding algorithm, and the system will send out false alarms continuously. However, the past visualization suppresses this fault by only displaying the median frequency of the interconnection. (3) Some dedicated algorithms are not sufficient to resolve the issues. Take the same FDR unit misplacement issue as an example. Although the dedicated islanding algorithm [5] can tell this unit is “islanded” from the Eastern Interconnection (EI), it will constantly exclude it from the EI, rather than intelligently reset it into QUEBEC.

The purpose of the FNETVision system is to create an adaptive visualization system to monitor and analyze the fast growing, large volume wide-area measurement data. With the FNETVision system, the FNET administrator can quickly identify a potential issue from the large-volume WAMS data, and track the cause of the issue accordingly. During the past few months, the FNETVision system was developed and deployed across the FNET system. The paper describes how the FNETVision system is designed and presents 2 case studies to show how to use it to identify and resolve the issues under big data scenario.

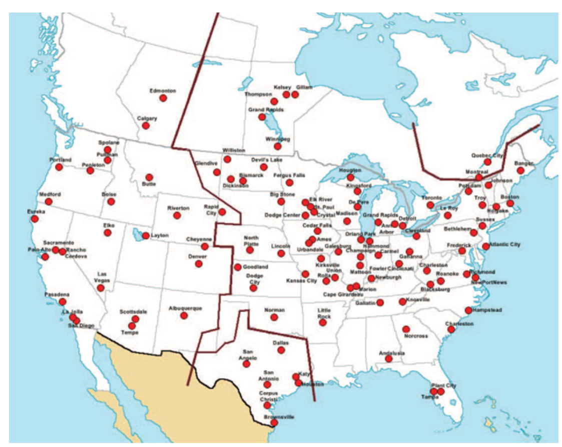

Figure 1. The map of FDR locations in North America

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II. Frequency Monitoring Network Phasor Data Concentrators Architecture

The FNET system is a wide-area sensor network consisting of highly accurate FDRs and several central processing servers [3], which functions as PDCs. Each processing server serves as an independent PDC and there exists data forwarding between PDCs. In general, the PDCs in the FNET system are categorized into two groups, such as *concentrators* and *analyzers*. Figure 2 shows the hierarchy of the PDCs across the FNET system.

A. Concentrators

The first group includes the concentrators. A concentrator collects data from FDR units, store the data, and forwards the data to several PDCs in the second group. In the real FNET system, to ensure the stable running of the concentrators, there is no time-consuming calculation on the concentrators, however there are some off-line statistics analysis providing the data quality summary of the active FDR units on daily basis.

B. Analyzers

The second group includes the analyzers. Upon receiving the data forwarded by the concentrators, an analyzer performs simple real-time calculations such as event triggering [3, 4], oscillation triggering [5], line trip triggering [6], and islanding triggering [7]. If a power system event is triggered, the analyzer will invoke several more complex, time-consuming event detection programs to calculate, summarize, and persist this event [3, 4]. In the past few years, the FNET system has completed the transformation to the openHistorian system [6, 8]. At present, the openHistorian serves as an analyzer that handles the real-time disturbance triggers.

III. FNETVision System Architecture

The FNETVision system is built upon the openHistorian and Grafana visualization framework [9]. It consists of three main modules. The first module is the ***Historian*** module. It provides an efficient time-series historian database that stores the historical measurement data. The second module is the ***Interface*** module. It is built upon the openHistorian SDK. It abstracts the data extraction operations in the openHistorian and exposes the Grafana APIs to the local address. The last module is the ***Visualization*** module. It utilizes the Grafana visualization framework to generate the plots of the frequency data. This section will discuss the design of these three modules and their adaptability in detail.

A. Historian Module

The *Historian* module in the FNETVision system uses the openHistorian as the backend database. In the past few years, FNET has transferred to the open source PDC platform-openHistorian. The openHistorian is an efficient time-series historian database. It utilizes the key-value pair (KVP) B+ tree as the database structure and efficiently stores the time-series data by tag, timestamp, and value in multiple .d2 files, where each .d2 file contain a chunk of data. The openHistorian also merges the .d2 files and reduces the overall storage efficiency on daily basis. The openHistorian provides many APIs to let the outer programs to interact with itself. These APIs include getting data, inserting data, updating data, and deleting data. Figure 3 shows the openHistorian system structure.

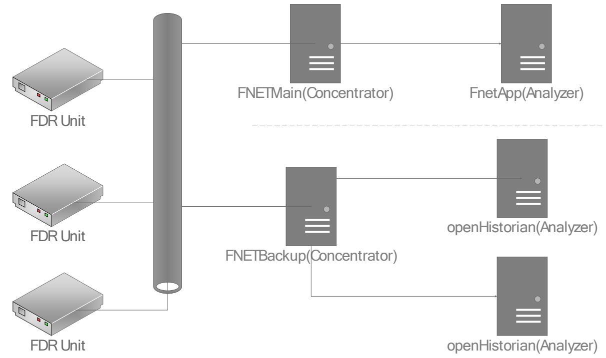

Figure 2. The hierarchy of the PDCs across the FNET system

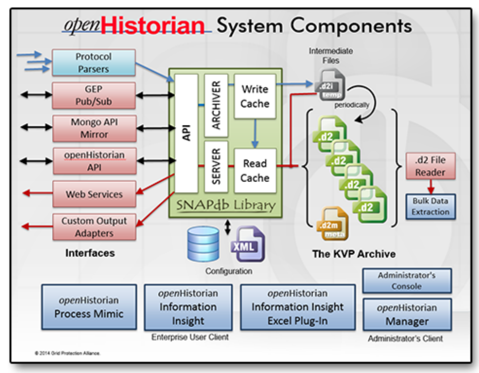

Figure 3. The openHistorian System Structure

B. Interface Module

Typically, in the Grafana framework, a data source is defined to retrieve time-series data from the backend historian database. In the FNETVision system, the data source is a web-based component that uses the openHistorian API to get data from the openHistorian. In particular, the openHistorian provides a dedicated Grafana API to enable the Grafana user to retrieve time-series data from the historian database using SQL style queries (e.g. "FILTER TOP 5 ActiveMeasurements WHERE SignalType LIKE '%PHA' AND Device LIKE 'SHELBY%' ") [10]. After the query request is sent to openHistorian, it will retrieve the data chunk from historian and pack it as JSON format, then append it as the response context, and finally send it back to the Grafana framework.

C. Visualization Module

The Grafana *Visualization* module mainly consists of two parts. The first part is the **data source**, which is described above. The user sends query command via the data source to the openHistorian and gets the returned JSON format data from openHistorian. Then the data source sends the JSON format data to a formatter, which unpacks the JSON data into Grafana specified data structure. The second part is the **dashboard**. The dashboard provides various visualization plugins, such as graph, table, heat map, etc. The administrator can choose a visualization plugin and configure the template of the visualization using SQL-style query language. The Grafana framework also contains an internal database, which saves the configuration of the templates for continuous use. In the Grafana framework, upon unpacking the JSON data, the *Visualization* module maps it into all the pre-configured templates.

IV. FNETVision Implementation

The initial phase of the FNETVision system includes 10 sub-visualization system. In particular, the FNETVision system includes Eastern Interconnection (EI), Western Electricity Coordinating Council (WECC), Electric Reliability Council of Texas (ERCOT), and Quebec Interconnection (QUEBEC). The FNETVision system contains 4 raw frequency graphs, and 4 5-seconds DfDt graphs of 4 interconnections respectively. Finally, it includes the heat maps of EI and WECC to statistically summary their frequency characteristics for data quality monitoring.

A. Raw Frequency Graph

The core function of the FNETVision system is to visualize the raw frequency measurement data by interconnection. The purpose of the raw frequency graph is to create the detailed visualization of the frequency measurements for the system operators. The Grafana framework enables a “click & display” feature for the “graph” model. By clicking at the legend of a single unit, the framework generates an independent raw frequency graph of this unit. Due to these features, the raw frequency graph is crucial to the inner and inter power systems knowledge discovery. Figure 4 shows the sample raw frequency graph of EI, while Figure 5 shows the sample raw frequency graph of Unit #684 in EI when the NA-EI-684:F legend is clicked.

B. 5-second DfDt Graph

The second function of the FNET Visualization system is to calculate and visualize the 5-second DfDt, which is widely used by the disturbance detection algorithm [16]. In the practical system, the 5-second DfDt is not stored in the historian database. The Grafana framework invokes the API to retrieve the raw frequency from the historian, calculates the 5-second DfDt, unpacks it into the Grafana data structure, and maps it onto the graph. Using the DfDt graph, the system operator can know the sequence of the FDRs that trigger the disturbance. Figure 6 shows the sample DfDt graph of EI.

C. Heat Map

The last function is the statistical display. This function is realized using the heat map template. A heat map summarizes the distribution of the raw frequency data and maps it onto a grid-based graph. In the heat map model, the Grafana framework sends the data retrieval request to the historian, gets the raw frequency data from the historian, summarizes the distribution of the raw data, and maps it onto a grid-based graph. As shown in Figure 7, the heat map divides the raw frequency data into several intervals (i.e. 60.000Hz-60.005Hz, 60.005Hz-60.010Hz, etc.). When summarizing the raw frequency data, the heat map model extracts the system medium frequency and counts the number of frequency values in each interval. Then, the model calculates the percentage of the number of values in each interval with respect to the total number of values. Finally, the model assigns the color to these intervals according to the occupancy percentage. The highest gets the “white” color, while the lowest gets the “red” color. In this way, the system operator can get a brief overview of how the FNET system frequency is distributed. When a disturbance happens, the system operator can observe a more chaotic heat map, which can serve as an issue indicator.

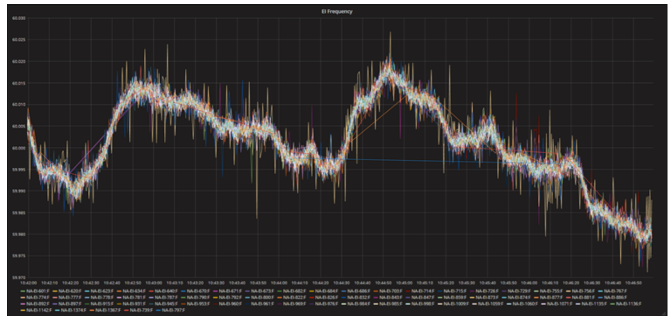

Figure 4. The raw frequency graph of EI

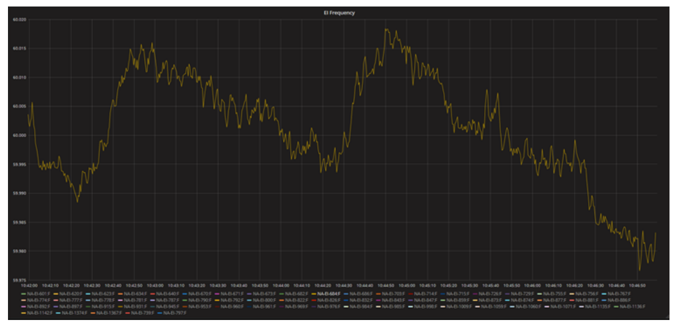

Figure 5. The raw frequency graph of Unit #684 in EI

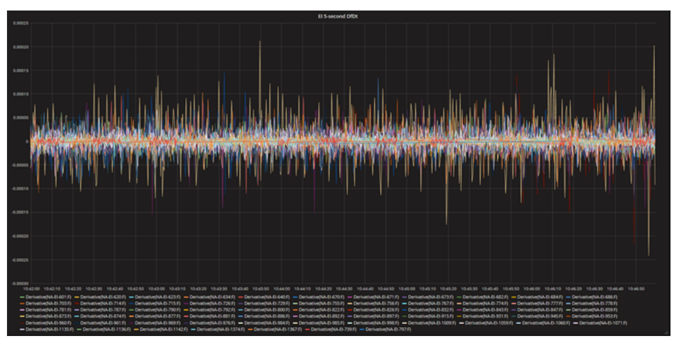

Figure 6. The DfDt graph of EI

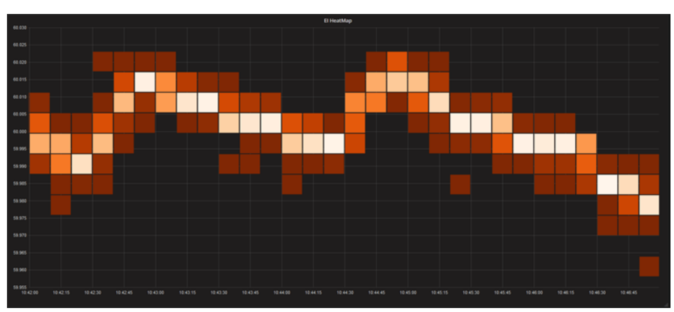

Figure 7. The frequency heat map of EI

V. CASE STUDIES

In this section, 2 cases are presented to illustrate the knowledge discovery process via the FNETVision system. These 2 cases represent the examples of FDR data quality assessment, and FDR misplacement respectively.

A. FDR Data Quality Assessment

The data quality is one of the core concerns in the WAMS. The quality of the measurement data usually influences the disturbance detection accuracy and the time-series data retrieval efficiency. Using the FNETVision system, the system operator can easily identify the bad data quality issue.

Take the bad data issue of FDR Unit #716 in EI as an example. Until 10/10/2017, the unit #716 had been keeping triggering the oscillation algorithm and sending out multiple "oscillation" reports [17].

Using the FNETVision system, the system operator trends the raw frequency data, and the 5-second DfDt of EI. As shown in Fig. 8, the raw frequency data of Unit #716 contains relatively bigger noise than any other FDRs in EI system. The worse part is- the noise data resembles the curve shape of a typical oscillation. When it is trended for longer time, the graph shows the issue existed from more than 1 month. As shown in Fig. 9, the 5-second DfDt of Unit #716 is **25 times** greater than the system average value, which is **1**. In Fig.10, rather than concentrated, the red-colored cells are widely spread out, which suggests that noise exists in the EI system.

These facts explain the reason why the Unit #716 kept triggering the oscillation detection system. It was the oscillation-like noise data that kept triggering the oscillation detection system and most of the oscillation reports caused by this unit were fake oscillations reports. After we disabled the real-time data stream from Unit #716, the issue was resolved.

B. FDR Misplacement

As a distribution level WAMS, our FDRs are hosted by hosts around the world. The power systems around the world are complicated and sometimes it is hard to specify which power system an FDR is actually belongs to. Take the 4 major North American interconnections as an example. According to [11], the interconnections in North America are relatively complicated. Take the ERCOT as an example. While most of the Texas area are covered by ERCOT, there are small areas at the northern and eastern Texas that are operated by South west Power Pool (SPP) and SERC respectively [11], which are connecting to the EI by AC line. Similarly, at the Northeastern USA, there are some areas managed by The New Brunswick System Operator (NBSO), which is connecting to QUEBEC, rather than the ISO-New England, which is connecting to EI.

In the real case, the islanding trigger reported continuous islanding event of Unit #1068 (Caribou, ME, 04736, (Latitude: 46.831311, Longitude: -68.050836)) when it first connected to the FNET data center. After examining the raw frequency data graph of EI the system operator first confirmed the islanding event and temporarily disabled the data streaming from Unit #1068, then brought it back online couple of hours later. However, in the next few days, the Unit #1068 triggered the islanding algorithm again. After comparing the raw frequency data of Unit #1068 and the median frequency of another 3 interconnections. The data from #1068 was found to resemble the system median of the QUEBEC. As described above, this area is managed by the NBSO, which belongs to QUEBEC. Previously, the islanding trigger only reports the "islanding" of the unit but it cannot tell which IC it belongs. Using the FNETVision system, the misplacement issue was quickly discovered and resolved, which prevents more false alarms.

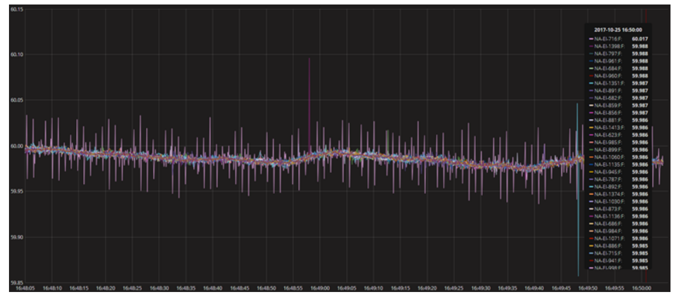

Figure 8. Example of FDR Unit #716 bad data quality

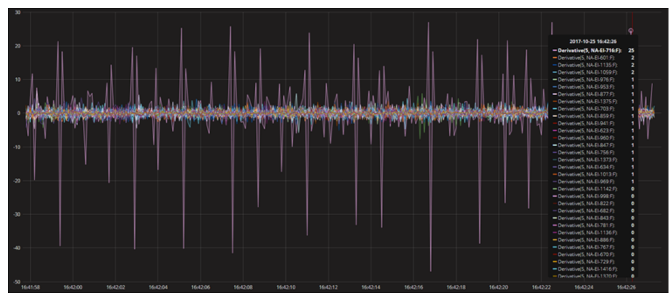

Figure 9. Example of FDR Unit #716 bad data quality (Raw frequency)

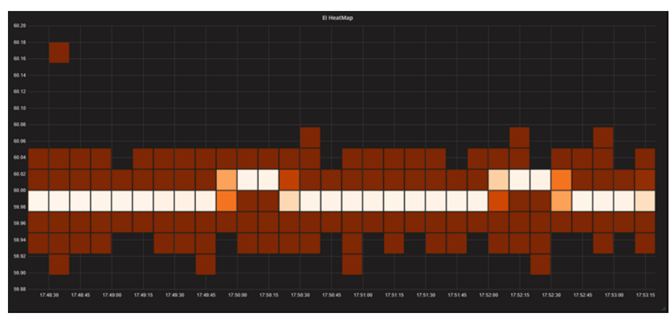

Figure 10. Example of FDR Unit #716 bad data quality (Heat map)

Figure 11. The raw frequency graph of EI

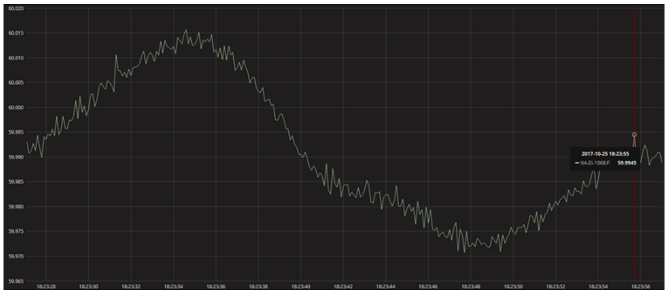

Figure 12. The raw frequency graph of FDR Unit #1134 at Caribou, ME

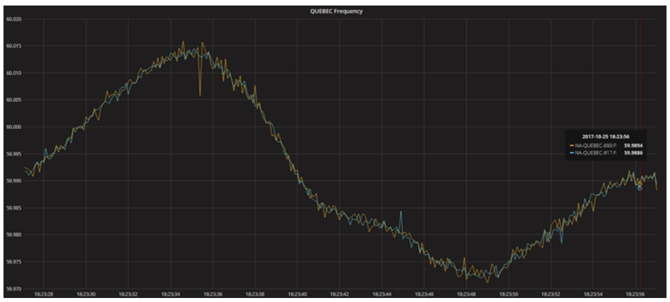

Figure 13. The raw frequency graph of QUEBEC

CONCLUSION

In this paper, the FNETVision system is developed to monitor the external and internal performance of the FNET system and discover the potential issues among large-volume FDR data. Specifically, this paper illustrates the functions of the three modules in the FNETVision system- the *Historian*, the *Interface*, and the *Visualization*. Then, this paper presents the implementation of the FNETVision system and the sample visualizations including raw frequency graph, 5-second DfDt graph, and heat map. Finally, this paper provides 2 case studies to show the big data knowledge discovery ability of the FNETVision system. The results suggest the FNETVision system is performant on discovering and helping resolve the potential issues within the FNET system. In the future, the FNETVision system will include the relative voltage angle visualization to aid the disturbance analysis such as generator trip, oscillation, forced oscillation, and line trip.

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REFERENCES

[1] Zhian Zhong *et al*., "Power system frequency monitoring network (FNET) implementation," in *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1914-1921, Nov. 2005.

[2] Natasha Vidangos *et al*., "Electricity in North America Baseline and Literature Review", U.S. Department of Energy, Washington, DC, Jul. 2016.

[3] Y. Zhang *et al*., "Wide-Area Frequency Monitoring Network (FNET) Architecture and Applications," in *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 159-167, Sept. 2010.

[4] G. Zheng, Y. Liu and G. Radman, "Wide area frequency based generation trip event location estimation," *2012 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2012, pp. 1-6.

[5] Y. Ye and Y. Liu, "Monitoring power system disturbances based on distribution-level phasor measurements," *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, Washington, DC, 2012, pp. 1-8.

[6] Z. Yuan *et al*., "Inter-area oscillation analysis using wide area voltage angle measurements from FNET," *IEEE PES General Meeting*, Minneapolis, MN, 2010, pp. 1-7.

[7] D. Zhou, Y. Liu and J. Dong, "Frequency-based real-time line trip detection and alarm trigger development," *2014 IEEE PES General Meeting | Conference & Exposition*, National Harbor, MD, 2014, pp. 1-5.

[8] Github.com, "GridProtectionAlliance/openHistorian: The Open Source Time-Series Data Historian", 2017. [Online]. Available: https://github.com/GridProtectionAlliance/openHistorian. [Accessed: 24- Oct- 2017]

[9] Grafana.com, "Grafana- The open platform for analytics and monitoring", 2017. [Online]. Available: https://grafana.com. [Accessed: 24- Oct- 2017]

[10] Grafana.com, "openHistorian Plugin for Grafana | Grafana Labs", 2017. [Online]. Available: https://grafana.com/plugins/gridprotectionalliance-openhistorian-datasource. [Accessed: 25- Oct_ 2017]

[11] Energy.gov. "Learn More About Interconnections | Department of Energy", 2017 [Online]. Available: https://energy.gov/oe/services/electricity-policy-coordination-and-implementation/transmission-planning/recovery-act-0. [Accessed: 25-Oct-2017]

[12] Y. Zhang *et al*., "Visualization of wide area measurement information from the FNET system," *2011 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2011, pp. 1-8.

[13] Y. Zhang, Y. Liu, L. Chen, J. Guo and Y. Liu, "Visualization of distribution level voltage magnitude pattern trend in EI system using FNET data," *2014 IEEE PES T&D Conference and Exposition*, Chicago, IL, USA, 2014, pp. 1-5.

[14] R. M. Gardner, G. B. Jordan and Y. Liu, "Wide-Area mode visualization strategy based on FNET measurements," *2009 IEEE Power & Energy Society General Meeting*, Calgary, AB, 2009, pp. 1-6.

[15] Z. Lin *et al*., "Application of wide area measurement systems to islanding detection of bulk power systems," in *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 2006-2015, May 2013.

[16] Y. Ye and Y. Liu, "Monitoring power system disturbances based on distribution-level phasor measurements," *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, Washington, DC, 2012, pp. 1-8.

[17] Powerit2.eecs.utk.edu, "FNET Oscillation Report", 2017. [Online]. Available: http://powerit2.eecs.utk.edu/fnet-oscillation-report/oscilreport.php?eventid=29506. [Accessed: 25-Oct-2017]