Final Scientific/Technical Report

Synchrophasor Visual Integration and Event Evaluation for Utilities (SynchroVIEEU) with High Penetration of Renewables

WORK PERFORMED UNDER AWARD NO.

DE-OE0000705

Hawaiian Electric Companies

P.O. Box 2750

Honolulu, HI 96840

Award Period of Performance: October 1, 2014 **to** September 30, 2017

Submitted: January 15, 2019

PRINCIPAL INVESTIGATOR

Shari Ishikawa

Smart Grid Program Manager

Hawaiian Electric Company

TEAM MEMBERS

Referentia Systems, Inc., DNV GL, Schweitzer Engineering Laboratories

SPONSORING PROGRAM OFFICE

U. S. Department of Energy

Office of Electricity Delivery and Energy Reliability

Via the National Energy Technology Laboratory

TABLE OF CONTENTS

ACKNOWLEDGMENT

The Hawaiian Electric Companies would like to thank the U.S. Department of Energy, in particular the National Energy Technology Laboratory, for their sponsorship of the SynchroVIEEU project. This material is based upon work supported by the Department of Energy under Award Number DE-OE0000705. We would like to extend our appreciation to our project sponsors, various technical managers and support staff.

Our SynchroVIEEU team of industry collaborators and vendor partners were instrumental in helping us achieve the success under the SynchroVIEEU initiatives. Together we all developed better appreciation and collaborative understanding of the needs and requirements to move toward the grid of the future.

The SynchroVIEEU team would like to acknowledge our strategic partners: Matthew Shawver at Referentia Systems, Inc., Dr. Greg Zweigle at Schweitzer Engineering Laboratories, and Ron Davis at DNV GL.

Finally, the work presented represents culminating efforts of a number of key personnel from across the Hawaiian Electric Companies who are endeavoring to make the system more reliable and cost-effective for our customers. Appreciation and acknowledgement is extended to our corporate executive sponsors, utility operations staff and to all the utility technicians and field staff supporting this effort. Without their dedication and ingenuity, these pioneering efforts would not have been successful.

DISCLAIMER

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

- ARRA – American Recovery and Reinvestment Act
- HECO – Hawaiian Electric Company
- HELCO – Hawaii Electric Light Company
- MECO – Maui Electric Company
- DOE – U.S. Department of Energy
- OE – Office of Electricity Delivery and Energy Reliability
- FOA – Funding Opportunity Announcement
- SCADA – Supervisory Control and Data Acquisition
- GIS – Geographic Information System
- SEL – Schweitzer Engineering Laboratories
- SynchroVIEEU – Synchrophasor Visual Integration and Event Evaluation for Utilities with High Penetration of Renewables
- NASPI – North American SynchroPhasor Initiative
- PMU – Phasor Measurement Unit
- EMS – Energy Management System
- SOPO – Statement of Project Objectives
- PMP – Project Management Professional
- ROCOF – Rate of Change of Frequency
- DER – Distributed Energy Resources
- UFLS – Under Frequency Load Shedding
- IEEE – Institute of Electrical and Electronics Engineers
- LAN – Local Area Network

I. Executive Summary

The Hawaiian Electric Companies (Companies), operating independent grid systems on the islands of Oahu, Hawaii, Maui, Molokai and Lanai, have been contending with some of the highest levels of renewable generation from both utility-scale and distributed generation resources. Renewable penetration levels exceeding 50% of generation are some of the highest in the nation and are changing the system characteristics and requiring operational changes to grid management. The Companies have aggressively leveraged federal, multi-state and industry grant funding to demonstrate new technologies for monitoring, visualization, forecasting and analysis to inform transformation needs and to improve operational awareness, especially at the distribution level. As part of the American Recovery and Reinvestment Act (ARRA) supported efforts to facilitate integration of renewables, synchrophasor devices were deployed on the islands of Hawaii and Maui in 2010. The devices have potential to provide Hawaii Electric Light Company (HELCO) on Hawaii Island and Maui Electric Company (MECO) with additional information to support post-event analysis and to help quantify observed area-wide changes in voltage and frequency on the systems.

Consistent with the U.S. Department of Energy's (DOE) Office of Electricity Delivery and Energy Reliability (OE) FOA objectives, the goal of this project was to accelerate the integration of synchrophasor information into production grade data visualization and analysis platforms/models to inform timely, efficient and reliable operations of a modern grid in light of high penetrations of renewable resources. The project comprised a two-year development effort to investigate the integration and visualization of synchrophasor field data into production-ready transmission and distribution proactive modeling efforts and a common data analysis platform application currently being used by the Companies. Conceptually, the project was about getting the right data to the right people at the right time in an easily accessible and timely environment.

The project's efforts successfully included:

- A real-time, time-series and event data management and analysis capability[1] in place at the Companies, called T-REX. This production-grade capability, developed with Referentia Systems, Inc. (Referentia Systems) using grant funding, provided a central integration point to incorporate and better utilize and assess large volumes of synchrophasor information for informing planning and real-time operations, especially on grids experiencing elevated change due to

[1] The Companies use MATLAB to review, compare and organize the data.

high penetrations of variable renewable resources at both the transmission and distribution levels. Unlike traditional data management architectures, T-REX supports SCADA and non-SCADA data streams and the use of analytical software, such as MATLAB and Python, to perform real-time and bulk offline event data assessments and search routines.

- An enhanced Proactive Approach methodology developed with DNV using grant funding, utilized production-grade transmission and distribution modeling tools to conduct scenario-based simulation analysis and defines a process for analysis and validation. Results were innovatively linked to geographically referenced (GIS-based) visuals to readily communicate impacts and findings. Synchrophasor information was used to further investigate, validate and assess dynamic conditions and address questions that previously were unable to be verified.

The project team, led by Hawaiian Electric Company (HECO), included subsidiary utilities MECO and HELCO operating and managing a diverse mix of generation, infrastructure and operating environments; Schweitzer Engineering Laboratories (SEL), a leading provider of synchrophasor technologies and software solutions for utilities; Referentia Systems, an innovative software developer providing advance data management and informatics capability; and DNV, a global provider of strategic transmission and distribution modeling expertise.

This project provided for specific targeted objectives, including:

- Incorporation of synchrophasor data into a production-ready, integrated data collection platform (T-REX) with real-time SCADA and non-SCADA data streams;
- Establishment of data handling procedures to enable synchrophasor software to interface with a common data analysis platform;
- Investigation of software tool development for a first-of-its-kind integrated visual that incorporates synchrophasor data in combination with transmission and distribution modeling results, real-time forecasts and other distributed generation data for real-time operational awareness;
- Investigation of utilization of synchrophasor data to inform Proactive Modeling Approach of distributed generation and microgrid impacts on existing system operation, restoration and contingency capabilities;
- Contribution to national efforts in building collaborative utility-vendor partnerships; and
- Dissemination of lessons learned and addition of relevant capability to commercial grade products.

As part of the development process, utility end-users were engaged throughout the review and validation of this project. Because the utility workforce must be able to “test-drive” new software and systems, their understanding and evaluation of how these new features and capabilities will support their functional and business processes are necessary to progress forward. These steps and the lessons learned contributed to broader DOE goals promoting development of training material, guidelines and standards for using and incorporating synchrophasor technologies. This project also helped innovate in a way that reduced the utility’s transformational risk by leveraging and building enhancements within familiar environments and using established utility-vendor relationships with a strong track record of innovation, project management and successful project deployment capabilities.

Modernizing the grid requires intelligence. That intelligence exists not only in informational content but also in the ability of end-users to feel comfortable in using the information, gaining insight through hands-on training and confidence to rely on the automation to inform decisions. An important outcome at the end of this project’s two-year period was that synchrophasor information was accessible and integrated into existing production-ready visualizations previously used by utilities monitor variable resources and has contributed to informing modernization and advance microgrid infrastructure evaluation needs. In support of the DOE OE’s goals, this project was aimed at encouraging the utilization of diverse high fidelity grid data including synchrophasor data, within familiar, production ready environments to aid decision-making and to inform transformational change.

II. Objectives

The goal of the Synchrophasor Visual Integration and Event Evaluation for Utilities with High Penetrations of Renewables (SynchroVIEEU) project is to accelerate the integration of synchrophasor information into production-grade data visualization and analysis platforms/models to inform efficient and reliable operations of a modern grid in light of high penetrations of renewable resources. The purpose is to provide advancement of synchrophasor modeling techniques through the development of appropriate and reliable models that incorporate synchrophasor information and actual grid experience. Specifically, the SynchroVIEEU approach supports determining processes and procedures to incorporate data into current and new models, defining a functional process to interface with academic models and help utilities better utilize synchrophasor data to advance planning needs.

Federal funding on this project has helped utilities and supporting industries by enhancing the potential to improve real-time operations and grid transformation needs through promoting rapid integration of new data streams provided by synchrophasors into production-ready tools to support reliable and economic operation with high penetration of renewables. The SynchroVIEEU concept brought together various groups across the industry, encouraging utilization of diverse high-fidelity grid data including synchrophasor data within familiar, production-ready environments to aid decision-making and informs transformational change. The SynchroVIEEU team includes three distinct, utilities with immediate high penetration needs (HECO, MECO and HELCO), world-class strategic modeling expertise (DNV GL), an innovation provider of secure IT and data analytics capabilities (Referentia Systems), and a global leader in design, manufacture and support distribution and transmission services (SEL).

Project objectives included:

- Facilitating access and review of existing synchrophasor data in combination with other utility information for system forensics, model validation and informing scenario planning needs;
- Integrating synchrophasor data into the HELCO's production-ready, integrated data analysis platform (T-REX) with real-time supervisory control and data acquisition (SCADA) and non-SCADA data streams;
- Establishing data handling procedures to enable synchrophasor software to interface with a common data analysis platform;
- Investigating software tool development for a first-of-its-kind integrated visual that incorporates synchrophasor data in combination with transmission and distribution modeling results, real-time forecasts, and other distributed generation data for real-time operational awareness;

- Investigating utilization of synchrophasor data to inform Proactive Modeling of distributed generation and microgrid impacts on existing system operation, restoration, and contingencies;
- Contributing to national and regional synchrophasor efforts including the North American SynchroPhasor Initiative (NASPI) and build collaborative utility-vendor partnerships and capabilities; and
- Disseminating lessons learned and add relevant capabilities to commercial grade products.

III. Technical Approach

This project employed existing utility-vendor collaborations that had been forged over many years to inform development of emerging interest to explore integration of new data streams — including synchrophasors — to support reliable and economic operation with high penetrations of renewables. This required integration of synchrophasor information with other field data, forecast data and modeling results, enhancing the potential to improve real-time operations and grid transformation needs.

Project approach focused on development of software and logic to support event driven and search capabilities, incorporating synchrophasor data with current grid-level data, real-time solar and wind forecasting information, and other distribution infrastructure data. Software enhancements and computational platform improvements were identified for the T-REX common data management and analysis platform to integrate high-speed synchrophasor data and to make better use of the information for post-event forensics, model validation, and improved visibility to the grid.

The Companies have nearly 20 SEL synchrophasor devices (Figure 1) on Hawaii and Maui islands to investigate the value of wide-area system data and to gain operational expertise in setting up the data concentrator architecture (Figure 2). The devices were installed by the Companies and have been in the field for several years.

Table **1** provides a list of the devices and their locations.

Figure 1 – Photos of SEL phasor measurement units (PMUs)

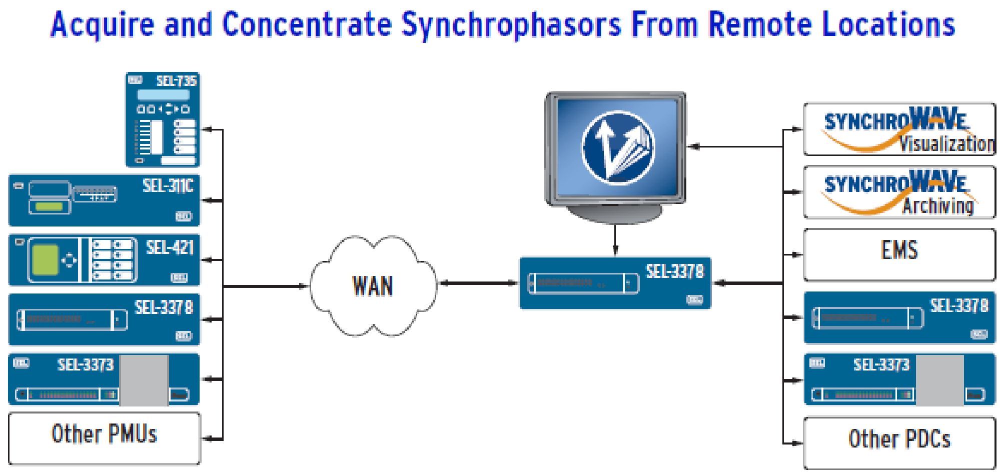

Figure 2 – Data concentrator architecture utilizing phasor measurement units (PMUs)

Table 1 – Summary of PMU equipment and locations in the Companies' service territories

Available Equipment	Pertinent Capabilities	Locations
SEL 451 Synchrophasors	Over 12 enabled field devices installed at generation substations over past 2-3 years on islands of Hawaii and Maui. Retrieving phasor data at sub second data streams.	Hawaii and Maui islands
SEL 421	Field devices deployed near wind farms	Hawaii island
SEL 3378	Field programmable data concentrators for synchrophasors	Hawaii and Maui islands
SEL 351	Various models from series but phasor data collection mode are not enabled. Majority are operating only in protective relay mode. Potential to enable data mode pending project results.	Hawaii, Maui, Oahu
SynchroWave PMU and PDC Software	Software for viewing synchrophasor data	Hawaii, Maui, Oahu

Work efforts included assessment of current Phasor Measurement Unit (PMU) data, providing T-REX, development of user needs-based enhancement plan, development of time-sequence visuals, completion of a system-level assessment of renewables-based grid impacts, process determination for new synchrophasor data incorporation, and development of technical training for data management techniques. The project followed the technical tasks proposed (see Appendix A) and the execution details are captured in Sections V to VII of this report.

To connect the various tasks conducted in this project, the results are organized for reporting purposes in the following three major categories: Synchrophasor Data Assessment and Review, Integrated Modeling and Visualization, and Technical Training and Outreach.

- **Synchrophasor Data Assessment and Review:** Focused on review and assessment of current PMU data on Maui and Hawaii islands and how best to utilize the information. Additionally, data obtained was leveraged for integration into a production ready common data analysis platform. (Section V)

- **Integrated Modeling and Visualization:** Focused on using and integrating synchrophasor data within the Proactive Modeling Approach and visualization tools to inform planning and grid modernization needs. Further supports determining processes and procedures to incorporate data into current and new models, defining a functional process to interface with academic models and help utilities better utilize synchrophasor data to advance planning needs. (Section VI)

- **Technical Training and Outreach:** Focused on supporting utility training and dissemination of lessons learned resulting from this project to a broader stakeholder community. Additionally, efforts focused on the development and documentation of the necessary training and bridging strategies in data management, advanced modeling strategies, and visualization techniques necessary to support the next generation grid. (Section VII)

IV. Project Milestones and Success Metrics

Project milestones and associated tasks are provided in Table 2. The original project period for the SynchroVIEEU project was October 1, 2014 to September 30, 2016. A twelve-month no-cost extension was executed in 2016 to extend the project end date to September 30, 2017.

Delays in the project resulted from a confluence of unforeseen regulatory and corporate merger issues and technical architecture upgrades for the EMS to address cybersecurity requirements that occurred late in 2014 through 2015. EMS upgrades and cybersecurity upgrades, which were completed at the end of 2015, postponed the schedule for the project. In addition, HECO executed a personnel change that resulted in the replacement of the project's Principal Investigator in November 2017. This further impacted progress on completing project close-out tasks. Unfortunately, these personnel changes and associated staffing constraints, unforeseen regulatory and corporate merger issues, and technical architecture upgrades to the Companies' EMS caused a delay in completing the final deliverables for the project.

Overall, the project tracked with proposal milestones despite unforeseen delays. The project executed on the five major tasks as defined in the Statement of Project Objectives (SOPO) over the project period.

This project has provided the following results:

- Facilitated access and review of existing synchrophasor data in combination with utility information for system forensics, model validation and informing scenario planning needs;
- Established data handling procedures to enable synchrophasor software to interface with a common data analysis platform;
- Investigated software tool development for first-of-its-kind integrated visual that incorporates synchrophasor data in combination with transmission and distribution modeling results, real-time forecasts, and other distributed generation data for real-time operational awareness;
- Informed Proactive Modeling and use of high appropriate generation data to assess microgrid impacts on existing system operation, restoration, and contingencies;
- Contributed to national and regional synchrophasor efforts including the NASPI and built collaborative utility-vendor partnerships and capabilities; and
- Disseminated lessons learned by utilities and added relevant capabilities to commercial grade products.

Table 2 – Milestone schedule of the SynchroVIEEU project

Milestones		
Task Title & Milestone Description	**Milestone Completion Date**	
	Completion Date	**% Complete**
2.1 – User Engagement & Data Review Report	2Q 2015	100
2.2 – Software Enhancement Plan & Priorities	3Q 2015	100
2.2 – Software Enhancement Report	1Q 2016	100
3.1 – Report on Use of Synchrophasor Deployment Readiness	1Q 2019	100
3.2 – Synchrophasor Deployment Readiness Plan	1Q 2019	100
5.0 – Abstracts to Industry Conferences	1Q 2015, 1Q 2016	100
5.0 – SEL Training Documents	4Q 2016	100

V. Synchrophasor Data Assessment and Review

As part of the user engagement and data review, this project provided support to compile and evaluate current use of the data, including accessibility and existing interface tools from SEL synchrophasors discussed in Section III (Technical Approach). Referentia Systems provided support to the Companies' staff in capturing and documenting user requirements and needs for using synchrophasor data. Results and summaries from user engagement interviews and data reviews were captured in the User Engagement and Data Review (Task 2.1), submitted to the U.S. Department of Energy in 1Q 2017 (see Table 2).

As part of the integration of synchrophasor data into a common data analysis platform, the T-REX time-series database platform was leveraged with a focus on the development of software and logic to support event driven and search capabilities. Analysis capability was expanded to include synchrophasor data, in addition to current grid-level data and real-time solar and wind forecasting information and other distribution infrastructure data. In collaboration with Referentia Systems, software enhancements and computational platform improvements were identified for the T-REX common data management and analysis platform to integrate high speed synchrophasor data and to make better use of the information for post-event forensics, model validation and improved visibility to the grid.

An enhancement plan and priorities were developed in collaboration with Referentia Systems, SEL and the Companies based on the use cases. Software enhancements were developed and demonstrated on separate T-REX servers to minimize risks on production platforms. A summary of these findings and further information was provided in the Companies' finalized Software Enhancement Plan and Priorities and Software Enhancement Report (Task 2.2), submitted to the U.S. Department of Energy in 4Q 2016 (see Table 2).

VI. Integrated Modeling and Visualization

The Companies, in collaboration with DNV, developed and applied a Proactive Modeling methodology, a scenario-based modeling approach to proactively evaluate changing grid conditions resulting from impacts of high penetrations of distributed generation. Additional validation data (power quality monitoring, protection devices, customer load data, irradiance monitoring) have been centralized in the T-REX database. Working with DNV, the Companies have improved the fidelity of production grade transmission and distribution models to better represent impacts of distribution level resources to the transmission models. The incorporation of synchrophasor data provided high-resolution, synchronized data associated with outage events at HELCO.

Software was used to develop time-sequence visuals that combined synchrophasor data with Proactive Modeling results. This helped to evaluate the value of adding synchrophasor data to such time-sequenced visuals to help evaluate, identify and prioritize issues that inform the Companies' mitigation strategies. The synchrophasor data on HELCO was incorporated within the Companies' modeling efforts to evaluate system impacts and provide recommendations for a future Oahu synchrophasor deployment. A summary of these findings and further information is provided in the report on Use of Synchrophasor Data to Improve Modeling and Benefits of Synchrophasor Data Visualization (Task 3.1), which was submitted to the U.S. Department of Energy in 1Q 2019 (see Table 2).

As part of informing of grid modernization strategies (Task 3.2), the Companies used existing transmission and distribution models to inform expansion of synchrophasors or other high-frequency monitoring devices. The system level assessment looked at how changing local grid conditions with increasing levels of DER impacted the island grids. Based on the Proactive Modeling results, the Companies worked with SEL and DNV to identify appropriate synchrophasor products that will enable appropriate device programming to capture distribution level issues. A summary of these findings and further information is provided in the report on Recommended use of Synchrophasor and Distribution Deployment Plan, which will be submitted to the U.S. Department of Energy in 1Q 2019 (see Table 2).

VII. Technical Training and Outreach

As part of the SynchroVIEEU technical training and outreach (Task 5), the Companies participated in industry conferences, sharing their insight with a larger stakeholder community. These presentations included providing lessons learned (good and bad) for the project so others could gain insight into the application of synchrophasor data within their own software systems and needs (see Appendix B). Abstracts related to these public presentations were submitted to the U.S. Department of Energy in Q1 2015 and Q1 2016 (see Table 2).

The Companies also shared use cases and enhanced visualizations, as well as participated in SEL training and DOE meetings (as required). The development and documentation of the necessary training and bridging strategies in data management, advance modeling strategies, and visualization techniques necessary to support the next generation of the Companies' grid were also conceived as part of this project. Copies of the training materials created were submitted to the U.S. Department of Energy in 4Q 2016 (see Table 2).

VIII. Accomplishments and Conclusions

The two-year development effort for the SynchroVIEEU project investigated the integration and visualization of synchrophasor field data into transmission and distribution proactive modeling efforts and into a common data analysis platform application currently used by the Companies. The effort focused on getting the right data to the right people at the right time in an easily accessible and timely environment. The project leveraged two recently-developed solutions and implemented capabilities – T-Rex and Proactive Modeling. The project approached innovation in a manner that reduced the transformational risk by leveraging and building enhancements within familiar environments, and by using established utility-vendor relationships. The project team's work encouraged utilization of diverse high-fidelity grid data including synchrophasor data, within familiarenvironments to aid decision-making and informs transformational change. Results and lessons learned have been shared during industry venues, including NASPI.

a. Major Activities Completed & Goals Achieved

The primary achievement of this project involved accelerating the integration of synchrophasor information into production-grade data visualization and analysis platforms/models to inform efficient and reliable operations of a modern grid in light of high penetrations of renewable resources. To achieve this, the project team, which included the Companies, Referentia Systems, SEL and DNV, tracked the project's status through five major goals: (1) Project Management and Team Coordination, (2) Synchrophasor Data Assessment and Review, (3) Integrated Modeling and Visualization, (4) Advancement of Synchrophasor Modeling Techniques, and (5) Technical Training and Outreach.

Results include:

- Project meetings (kick-off, coordination conference calls, close-out, DOE meetings);
- Updated PMP, budget, and schedule documents;
- Submitted quarterly project status reports, as specified by the DOE;
- Event-driven, multi-data trending and search scripts;
- Utility user selection capability to access and tailor analysis scripts;
- Secure interface to SEL device concentrators to automate upload needs;
- Computational enhancements to handle sub-cycle data (10 to 30 samples/second);
- Custom data displays to enable review, search, query and tailoring of data by users;
- Submission of the User Engagement and Data Review report;
- Submission of the Software Enhancement Plan and Priorities report;
- Submission of the Software Enhancement Report;
- Development and submission of the Training Documentation;
- Enablement of combined analysis of synchrophasor data with production-ready transmission and distribution models;
- Creation of visuals to share results and inform decision making;

- Captured benefits and efficiencies that helped to inform adoption of technologies;
- Recommendations for Synchrophasor and Distribution Deployment Plan;
- Submission of Use of Synchrophasor Data to Improve Proactive Modeling report;
- Submission of Benefits of Visualizing Synchrophasor Data report;
- Summarization of complimentary synchrophasor activities;
- Submission of Utility Participation Report;
- Submission of abstracts to industry venues;
- Completion of SEL on-site product training;
- Completion of SEL synchrophasor classroom training;
- Development of utility outreach and training schedule; and
- Submission of enhance visualization and utility training and presentation documentation.

b. Major Findings, Metrics & Developments

The Synchrowave software is a tool for accessing high-fidelity PMU data (i.e., synchrophasor data) and incorporating this information into the HELCO planning process for Operations. This is of value in analyzing transient and dynamic system events that lower resolution SCADA data does not capture. As the power system continues to evolve, this higher resolution data will be of increased value to enable the validation of power system modeling of transient and dynamic behaviors, as well as allow the analysis necessary for future resources to interconnect and provide verification and validation of acceptable resource and system performance.

The PMU's rate of gathering data (current sensors are 60 samples per second) is much faster than the current SCADA system (current sensors are one sample per 2 seconds). However, the clock of the PMU is controlled by the system frequency. PMU data allows for a more detailed analysis before, during, and after system events. Figure 3 below, which is from a lightning strike that occurred on the island of Hawaii in September 2015, highlights this in the rate of change of frequency (ROCOF) and the actual frequency change experienced by the event. The graph shows that the SCADA system only detected a frequency drop of 59.95Hz while the PMU's detected a frequency drop of 59.75Hz at the same time.

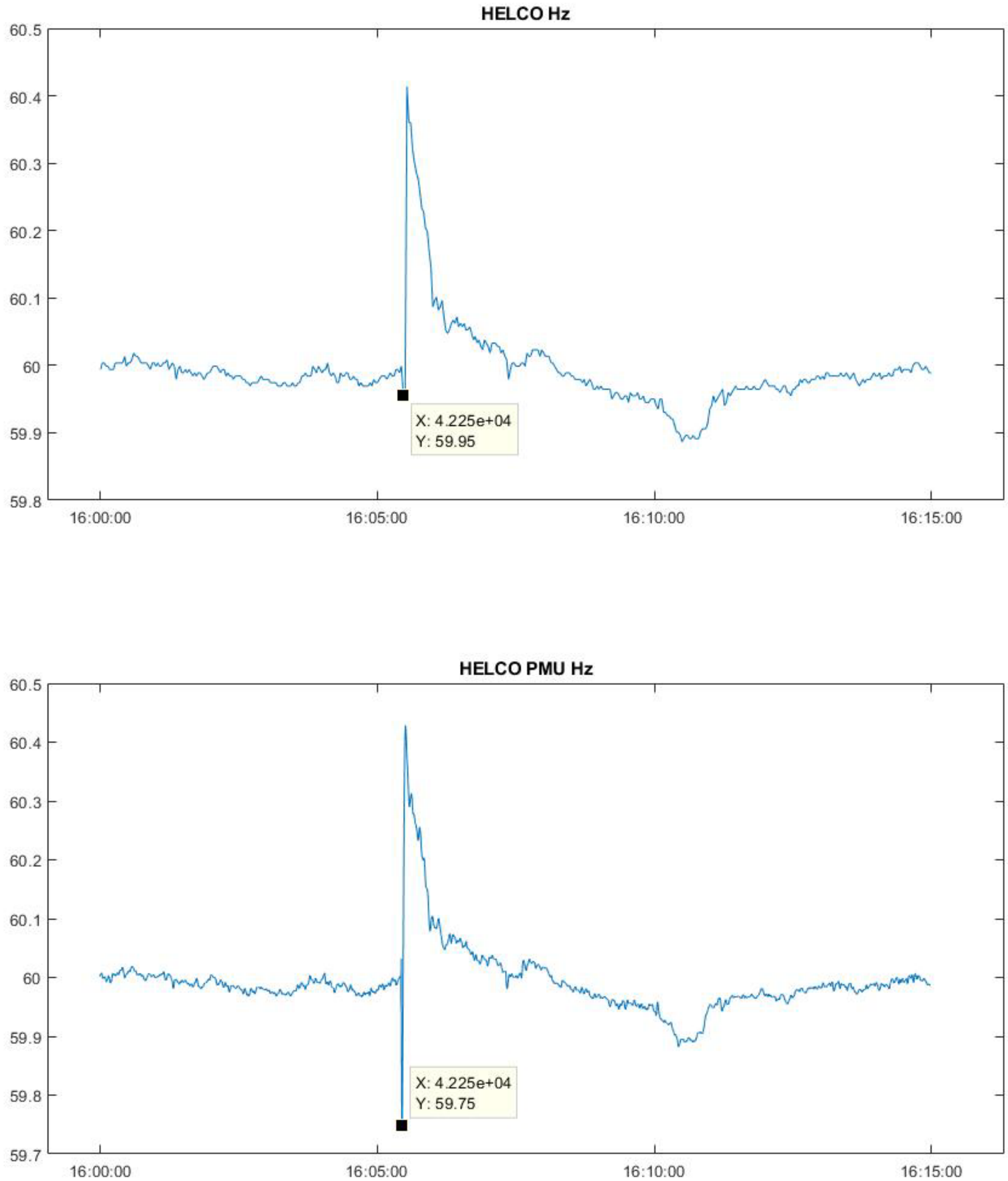

Figure 3 – HELCO ROCOF Incident (September 2015)

The data from the PMU with its greater resolution provides accurate record of the system voltage and frequency transients during faults and contingencies. Additionally, there are PMU's that can actually capture system data at even higher rates which include 120 messages per second and 240 messages per second.

HELCO engineers have analyzed the PMU data which has been leveraged to validate proper operation of protection schemes and define disturbance ride-through criteria. The rate of change of frequency history was utilized to inform the design of a rate of change of frequency trigger to enhance the underfrequency load shed protection scheme.

This high resolution synchrophasor data has also proved valuable in providing a detailed record of system impacts which enhanced understanding of the impact of distributed resources (DER) on the bulk system during faults and contingencies. Through post-disturbance review of PMU data, sudden change in frequency during solar production hours at DER instantaneous trip points for voltage and frequency (i.e., 59.3 Hz, 60.5 Hz) were captured and provided concrete data confirming the loss of DER and contribution to system disturbance conditions.

The synchrophasor data is also being leveraged by the system operations to provide phase angle data and observed frequency instabilities to inform switching actions and observe system behavior during disturbances.

An example of this took place in June 2018, which impacted roughly 7,600 customers in four distinct areas on Hawaii Island. Figure 4 depicts the UFLS event following an unexpected trip offline.

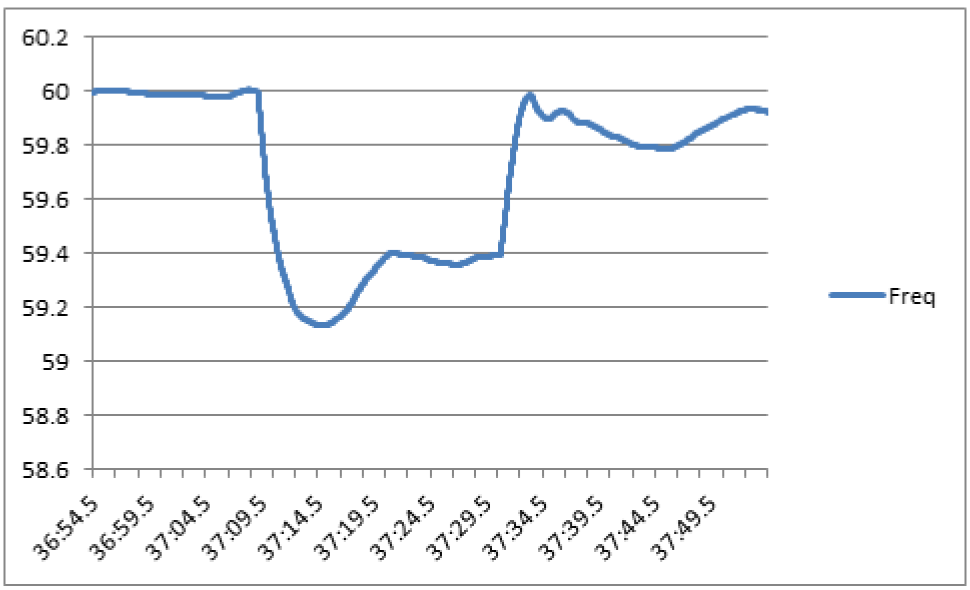

Figure 4 – UFLS Event (June 2018)

The normal operations for these circuit locations are set to operate at 59.5Hz with a 20-second time delay. By observation of at the synchrophasor data, relays operated properly, and settings were appropriate as frequency returned to 60.0 Hz. Frequency then dipped back down to 59.8Hz as one circuit location reduced output following the plants' droop response (Figure 5).

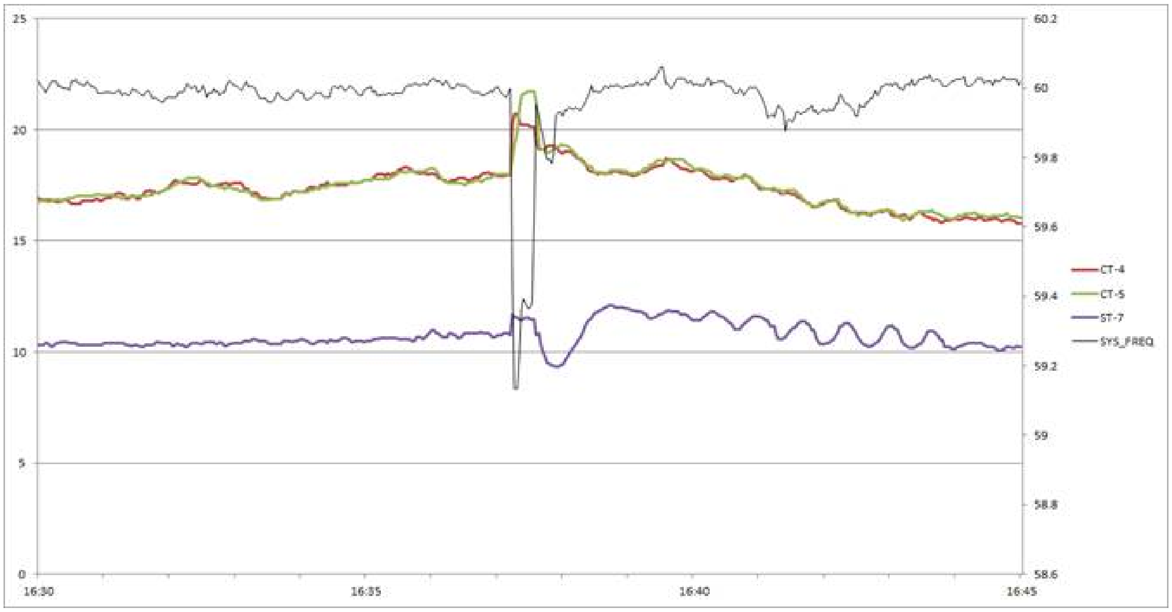

Figure 5 – System frequency and generator response on Hawaii Island.

In December 2018, synchrowave data was able to show that system-issued close commands, which had been erroneously sent a timeout following a circuit line opening, were actually functioning properly with the circuit breakers closing and re-opening correctly. Figure 6 provides a visual representation of this success metric during this event.

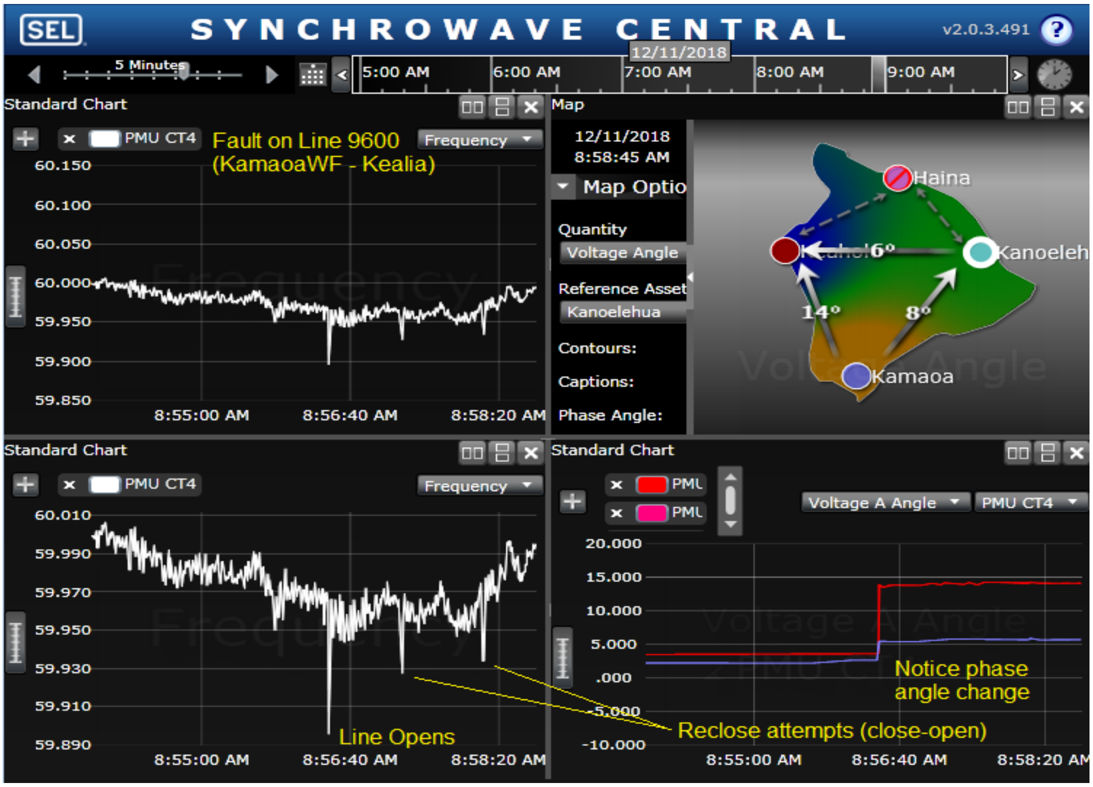

Figure 6 – Circuit Reclose Attempt Success Metric (December 2018)

The new synchrowave display allowed the system operators at HELCO to view the system's state at a high resolution (60x per second). The viewing duration may need to be adjusted to allow for a faster flow of information as some system operators missed the initial reclose attempt. Subsequently, system operators could have saved one minute in the power restoration time and could have classified the outage as momentary (<5 minutes).

In total, there have been five UFLS events on Hawaii Island since 2017, all occurring following the loss of the geothermal power plant. With the application of the synchrophasor data for the Companies' system operators to leverage the data to gauge the causes and remediation process, it is clear that additional studies are needed to identify system risks, reactive power requirements, and solutions which may include pre-contingencies dispatch requirements. System operations can no longer rely on historical grid behavior to understand the impacts of contingencies and outages. To date, the UFLS scheme appears to be working well; however, the Companies will continue to use reviews of operational data and performance to make any refinements and adjustments.

c. Lessons Learned

Through the use of PMU data, the impact of a relatively small amount of DER installed with historic IEEE 1547 trip settings can be quantified with actual operational data. Post-disturbance data provides insights useful for adjusting ride-through requirements and design criteria for phase angle jumps, over/under frequency and over/under voltage, and involvement of phases. The rate of change of frequency data has been used to identify its increase with a change in resource mix.

The Companies have found, through the various events captured and reviewed with the synchrophasor data, that they need to avoid tripping on ROCOF when returning from high frequency due to loss of load. This would avoid shedding customers unnecessarily and prevent the frequency from rising repeatedly when it is trying to return to a normal state. The Companies plan to work with a consultant to determine the proper restraint mechanism. Although the ROCOF setting can be difficult to determine, leading to a potential for a false-trip, the frequency set point is a backup.

One significant lesson learned was that the Companies need a common platform for all of their data to reside or at least one platform to acquire all relevant data. At this time, the Companies have many different data sources and multiple data repositories. Gathering all data into one software package is daunting, and this task creates inefficiencies by requiring utility personnel to spend time gathering data which takes away time from performing actual analysis. This project enabled utility computer engineers to evaluate project management processes for data analysis projects at this scale. A key observation is that the Companies' data sets are fragmented and improved capability to link various data sets would be valuable.

HELCO Operations staff also observed the benefits of enhanced network connectivity from the Systems Operations network (also known as the Energy Management System LAN) to the corporate network or the enterprise LAN, including the sending of grid data in an automated fashion from one network to the other (see Section d - Benefits & Significance of Accomplishments).

d. Benefits & Significance of Accomplishments

<u>T-REX</u>

The Company's network topology is made up of a corporate LAN (enterprise) network and an Energy Management System LAN (EMS) network with no path between the two. The majority of archived SCADA data resides only in the EMS network which limits access to this valuable data. The T-REX software opens a path for all corporate LAN users to be able to quickly view plots of SCADA data and export it for further data analysis and evaluation. This capability gives all Company employees with corporate LAN and T-REX software access that ability to analyze historical events, load trends, and any other analytical work that historical SCADA data could be used for. Prior to T-REX, a data request requiring specific SCADA data would need to be extracted from the SCADA archive by an individual with access to the EMS network and use of a single data extraction tool by a single user one extraction at a time. With the T-REX capability, any corporate LAN user could have the capability to acquire the data they need thus increasing the number of employees with data access from one to the total number of employees needing access.

The integration of synchrophasor data into T-REX will add value in that it will combine the 2-second resolution SCADA data with the high resolution (60 samples per second) phasor data to provide a single location for comparative event analysis. This integration and temporal alignment of the data eliminates the need to separately perform these tasks, thus allowing analytical tasks to proceed faster.

Access to historical data has high value in analyzing the behavior of the power system as it evolves over time. With generation resources changing to smaller synchronous machines and distributed inverter-based power and storage systems, behavior of the various types of resources in the aggregate is of high interest to the Companies. It is of great value to be able to capture how the system has been performing historically and to illustrate the changes to the system and how they affect the power system as a whole. Access to actual measured data is a valuable resource for achieving this analytical capability. As the Companies' power systems continue to evolve, and at a more rapid pace than previous years, this data and access to it will only be of increased value to enable the analysis necessary to allow future resources to interconnect as well as provide verification and validation of acceptable resource and system performance. It is anticipated that other utility grid systems in the U.S. and elsewhere will require short-time scale gird performance data and analytical tools.

SYNCHROWAVE

The synchrowave software is a tool for accessing high resolution phasor power system data. This is of value in analyzing transient and dynamic system events that lower resolution SCADA data does not capture. The synchrowave data captured in recent months is currently being used to analyze system events that cause frequency excursions to determine the ROCOF the event caused. This information is useful for determining protection settings and ride-through requirements. Similarly, frequency and voltage transients are accurately captured to assess impacts from DER. This has been extremely valuable in providing concrete operational data confirming the impact of DER and need for certain operational and technical requirements to avoid negative impacts on bulk system reliability. The phasor data has also been useed in real time by the operators by providing phase angle separation information prior to closing in certain transmission lines. It enables the operator to be able to see the phase angle difference so that resources can be re-dispatched prior to the close attempt, and thus bring the separation to the level required to permit the breaker close. Observations in real time, during abnormal operating conditions, and post disturbance reviews have also brought to light frequency and phase angle instabilities which were not previously known to exist. With further integration of phasor data into the operators' actual real time displays, this capability for real time informed decisions based on phasor data will only increase.

e. Next Step Priorities

The next step priorities would be to further monitor the PMU data, and identify additional conditions which in real-time the operators need to be aware of (e.g., frequency inabilities). Islanding detection would be another valuable capability to incorporate. The use of PMU data to improve the benchmarks for system dynamics modeling is a high priority so that the Companies can develop the necessary solutions to provide reliable system operations in the future with displacement of conventional generation.

For the above to happen in an efficient manner, the Companies would benefit from an enterprise-level system operations and data analysis platform. Unifying the data into a common platform is the key next step as it can enable more efficient and consistent analytical tasks .

APPENDIX A: Summary of Project Tasks

Task 1: Project Management and Team Coordination

This task covered the administration and project/team coordination. Organization and project follows the SOPO and PMP. The team was organized as shown in Figure 7 – Project Team and Organization. HECO staff acted as primary project managers and leads.

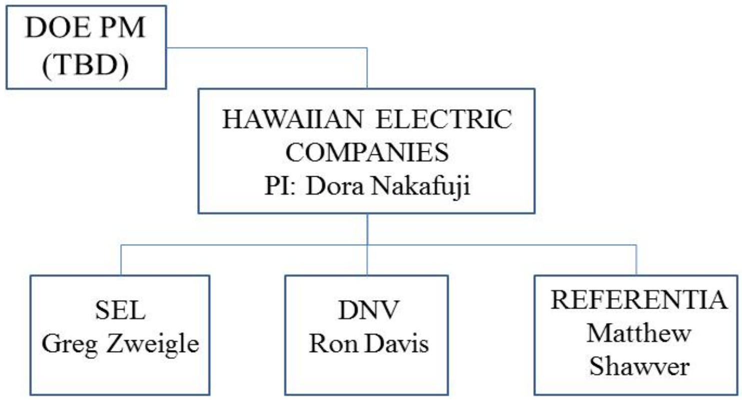

Figure 7 – Project Team and Organization

Task 2: Synchrophasor Data Assessment and Review

This task focused on the review and assessment of PMU data on Maui and Hawaii islands, and how best to utilize the information. The task also focused on integration into a production-ready common data analysis platform.

Task 3: Integrated Modeling and Visualization

This task focused on using and integrating synchrophasor data within the Proactive Modeling Approach and visualization tools to inform planning and grid modernization needs.

Task 4: Advancement of Synchrophasor Modeling Techniques

This task supported determining processes and procedures to incorporate data into current and new models, defining a functional process to interface with academic models and help utilities better utilize synchrophasor data to advance planning needs.

Task 5: Technical Training, Outreach and Reporting

This task supported utility training and dissemination of lessons learned resulting from this project to a broader stakeholder community.

APPENDIX B: Product or Technology Production

- North American Synchrophasor Initiative (NASPI) Workshop – March 2015

  The NASPI held a technical workshop to explore event playback and generator model verification using PMU data. The workshop reviewed why and how to perform these tasks using PMU data and compared the usability of the commercially available software tools for event playback and the accuracy and availability of generator model verification tools.

  A copy of the presentation can be accessed from the NASPI website, available at https://www.naspi.org/sites/default/files/2016-09/maui_electric_nakafuji_synchrovieeu_20150324.pdf

- T&D World Magazine Article – August 18, 2016

  Entitled, "Visibility Enables PV Integration", Dora Nakafuji published an article on behalf of the Companies discussing Hawaii's renewable energy goals, the current state of the electric grid, the need for more grid visibility, and the work of the SynchroVIEEU project and its significance for renewable integration.

  The article can be accessed via the T&D World Magazine website, available at http://www.tdworld.com/generation-renewables/visibility-enables-pv-integration

- Solar Power International (SPI) Workshop – September 12, 2016

  Entitled, "SPI Workshop – Integrating Distributed Energy Resources onto the Grid", this one-day workshop brought utility engineers and planners together with technology vendors, researchers, and manufacturers to explore the effective integration of distributed energy resources into the electric grid. Dora Nakafuji was a keynote speaker who addressed Hawaii's 100% renewable energy goals and the need for visibility through data modeling of wind and solar projects.

  A copy of the presentation is available from the SPI website at http://www.solarpowerinternational.com/wp-content/uploads/2016/09/N253_9-14-1300.pdf

- Smart Electric Power Alliance (SEPA) Article – September 15, 2016

  Entitled, "Making the elephant fly: Integrating distributed energy resources onto the grid in Hawaii", the article provides edited excerpts from the SPI Workshop that Dora Nakafuji presented at on September 12, 2016.

  The article can be accessed via the SEPA website, available at https://sepapower.org/knowledge/making-the-elephant-fly-integrating-distributed-energy-resources-onto-the-grid-in-hawaii/

- North American Synchrophasor Initiative (NASPI) Workshop – October 2016

  The NASPI held a technical workshop to explore event playback and generator model verification using PMU data. The workshop reviewed why and how to perform these tasks using PMU data and compared the usability of the commercially available software tools for event playback and the accuracy and availability of generator model verification tools.

A copy of the presentation can be accessed from the NASPI website, available at https://naspi.org/sites/default/files/2017-03/05_heco_nakafuji_SyncrhoVIEEU_NASPI_20161020%281%29.pdf

- Power and Energy Automation Conference – March 2016
- 19th Annual Georgia Tech Fault and Disturbance Analysis Conference – April 2016
- 70th Annual Conference for Protective Relay Engineers – April 2017
- Abstract titled Integrating Synchrophasors and Oscillography for Wide-Area Power Systems Analysis

A copy of the presentation can be accessed from the NASPI website, available at https://ieeexplore.ieee.org/document/8090033