

VELCO and VEC Pilot Project on Novel High-Resolution Point-On-Wave Monitoring for Transmission Event Analysis & Model Validation

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Abstract

Vermont is one of the top states in the country that has the highest penetration of distributed energy resources (DERs), and this penetration is expected to grow over the coming years. In 2024, Vermont Electric Power Company (VELCO) and Vermont Electric Cooperative (VEC) initiated a pilot project to explore a novel technology that leverages existing broadband communications networks to enable high-resolution, point-on-wave monitoring of their transmission system at key distribution system locations critical to transmission planners. The increase in DERs adds operational complexities and challenges for the transmission system, further exacerbated by a lack of visibility and high-resolution monitoring of the post-contingent behavior of the distribution system in response to transmission-level events. Further, federal regulations (i.e., Federal Energy Regulatory Commission (FERC) Order No. 901) will soon require all transmission planners and operators to model, validate, and study the impacts of inverter-based distributed energy resources on the performance of the bulk electric system. This pilot project demonstrated the ability to quickly deploy high-resolution monitoring throughout distribution circuits using the novel technology and the many benefits that instantly get realized once high-resolution, continuously streaming point-on-wave oscillography data is in place to enhance transmission coordination. This data is critical to improving transmission dynamic model validation, DER performance and requirement conformity evaluation to industry standards such as IEEE 1547-2018, and improved grid situational awareness. This paper will cover the details of the pilot project, the new technology, and the applications this enables for transmission utilities.

Keywords: oscillography, point on wave measurements, distributed energy resources, dynamic model validation, transmission monitoring, event analysis, situational awareness

Introduction

Vermont's electric grid is undergoing significant transformation, driven by the increasing integration of Distributed Energy Resources (DERs), Electric Vehicles (EVs), and Virtual Power Plants (VPPs). This change brings both exciting opportunities and substantial challenges in grid planning and operations. Currently, the lack of visibility beyond the transmission-to-distribution (T/D) substations creates gaps in real time insights.

Vermont Electric Power Company (VELCO), in its role as the Transmission Owner (TO), Transmission Operator (TOP), and Transmission Planner (TP), is essential to maintaining the reliability of Vermont's Bulk Electric System (BES). As the energy landscape transforms with the increased integration of DER and rising demand from electric transportation, and other factors, VELCO realizes the need to adapt to these changes while ensuring high-fidelity data across both geographically and temporally. To comply with regulatory requirements and safeguard grid stability [1], VELCO prioritizes enhanced monitoring capabilities, and continues improving transmission event analysis and model validation.

Utilities may lack the ability to conduct detailed assessments with information at higher data resolutions, which is needed now and going forward due to the transmission-level impacts of fast switching power electronic loads and generation resources. In this context, point-on-wave monitoring technology, utilizing

existing broadband infrastructure, offers a cost-effective option to comprehensive visibility of electric systems, the part of the grid missing high-resolution monitoring today. The installation of sensors and communications lines across the vast system is expensive and may be cost prohibitive (see Figure 1). As a result, the power system can have incomplete and discontinuous visibility.

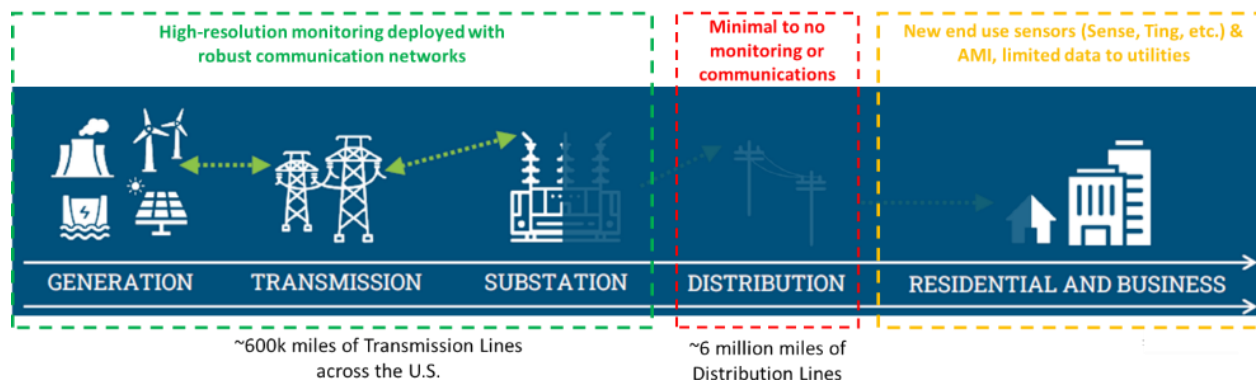


Figure 1: Illustration of Communication and Monitoring Coverage in the Power System Landscape

This paper evaluates the potential of a novel, high-resolution point-on-wave monitoring technology to enhance VELCO and VEC’s collaborative monitoring of transmission conditions. By providing high-resolution, time-synchronized data, point-on-wave monitoring can improve situational awareness, assist in transmission system planning, transmission event analysis, model validation, and enhance operational decision-making for VELCO and VEC. The purpose of this paper is to highlight the feasibility and potential benefits of this monitoring technology in supporting VELCO’s event analysis program, particularly in addressing the challenges posed by increasing DERs and more dynamic distribution networks. This paper will cover the technology’s data capabilities, its role in fault event analysis, potential use cases, and the development of recommendations to improve grid visibility and operational efficiency. The findings aim to shape the future of grid monitoring, ensuring Vermont’s electric grid remains resilient and reliable as it adapts to an increasingly complex energy landscape.

Point-On-Wave Monitoring Technology Capabilities

The point-on-wave monitoring technology measures and tracks electric system conditions using the cable broadband network. This technology combines field-deployed measurement devices with a near-real time¹ data collection platform to provide high-fidelity, time-synchronized visibility and monitoring of the grid. By leveraging the convergence of broadband and electricity sector networks, the technology uses broadband network uninterruptible power supplies (UPS) to measure voltage in the VEC distribution system. This approach enables the use of existing high-bandwidth measurement and telecommunications infrastructure, allowing for rapid and widespread adoption of near-real time monitoring in areas of the grid that have traditionally lacked visibility.

Monitoring Technology Overview

The point-on-wave monitoring technology presented here tracks the power status of over 325,000 broadband network power supply devices, offering an observational view of the electrical power status of thousands of locations. This low-resolution data provides an indication of power outages across the country. A unique difference between the point-on-wave monitoring technology data and advanced metering infrastructure technology is that 1) the technology measurements are located on the distribution system

¹ Near-real time: A process that operates with minimal delay, typically on the order of milliseconds, where responses occur with negligible latency, but not instantaneously.

rather than at end-use customer locations which can avoid concerns with customer data privacy, and 2) the communication of that information occurs securely over the broadband network with no utility involvement or investment in communication infrastructure.

The monitoring technology has identified an opportunity to further utilize broadband power supplies by installing low-cost, high-resolution monitoring sensors, known as "blue boxes," within these power supplies. These power supplies are part of the existing broadband communication networks which run alongside the grid throughout the country, and the power supplies draw power from the electric system to power the broadband network communication equipment such as backhaul fiber nodes. With high-bandwidth, low-latency fiber communications, the technology enables very high-frequency sampling of voltage waveforms from the distribution system, with continuous data streaming to a centralized monitoring and analytics platform, enhancing near-real time grid visibility. Figure 2 and Figure 3 show broadband equipment inside the industrial power supplies and their proximity to the electric distribution network.



Figure 2: Broadband Network Industrial UPSs

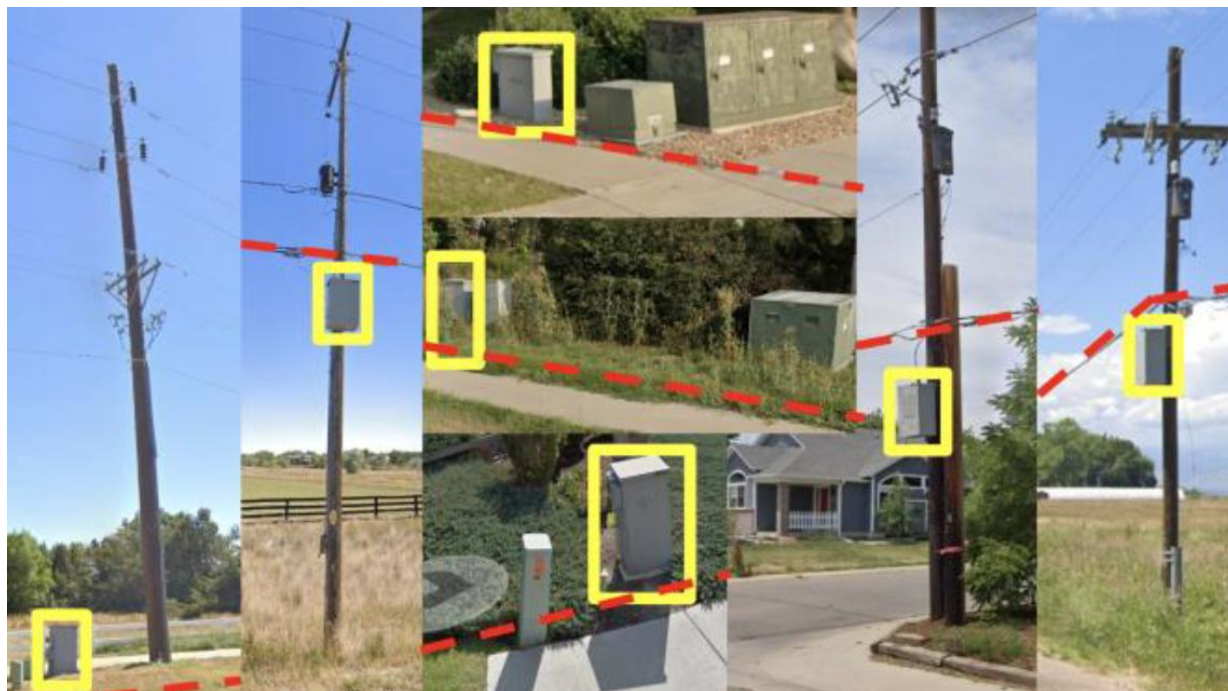


Figure 3: Broadband Network Adjacent to Electrical Distribution Network

Sensor Description

In terms of the overall electricity ecosystem, utility-scale generation and the transmission network have relatively comprehensive measurement coverage across different technologies, data resolutions, communication bandwidths, and geographic locations. Traditional transmission system monitoring equipment captures electrical quantities from potential transformers (PTs) and current transformers (CTs) located at substations. Remote terminal units (RTUs) capture low resolution measurement for the supervisory control and data acquisition (SCADA) system. Digital fault recorders (DFRs) and PMUs capture dramatically higher resolution waveform data and are time synchronized to the global position system (GPS). PMUs, for example, record frequency, voltage and current magnitude, and phase angle quantities typically up to 60 samples per second. Power quality meters and DFRs can detect power quality and other transient events and send brief waveform data snippets to analysis systems for post-event analysis. However, for installations outside the substation (ex: down a transmission line), PMUs and other high bandwidth devices face serious limitations, including installation capability and slower communication systems such as cellular networks.

The point-on-wave monitoring sensors can be installed at broadband UPS sites, with 88% of U.S. homes located within 1 km of these devices. These UPS devices provide battery backup for the broadband network during power outages, allowing the sensors to remain operational, thus enhancing utility restoration, safety monitoring, and post-event fault analysis. The sensors measure single-phase voltage waveforms at 10,000 samples per second, are GPS time-synchronized with microsecond accuracy, and include features such as lightning and motion detection, expansion ports for future sensors, and onboard flash storage. Data is streamed to the centralized monitoring and analytics platform servers with low latency, typically within hundreds of milliseconds.

The broadband network UPS locations serve as potential sites for installing the point-on-wave monitoring sensors, enabling high-resolution data monitoring of the electric system. These locations also host a point-on-wave monitoring power event notification system, as shown in Figure 4, which overlays broadband UPS and power event notification system sensor locations on the Vermont electricity network. Installing sensors

at these UPS devices would provide broad system coverage of the networks across Vermont, with sensor density aligned with broadband network distribution in densely populated areas.

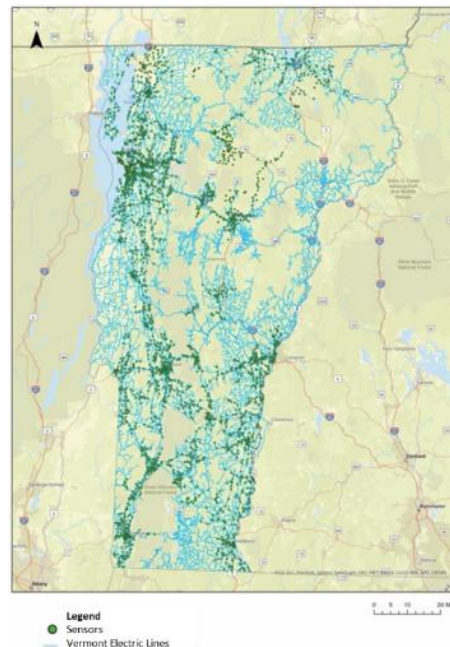


Figure 4: Potential Sensor Locations in Vermont

Technology Use Cases

The point-on-wave monitoring technology offers multiple use cases that can benefit VELCO's transmission system. It supports grid frequency and rate-of-change-of-frequency (ROCOF) monitoring, enhancing the detection of frequency deviations, and improving coordination of generation resources. Additionally, it aids in system-wide voltage monitoring by providing early detection of voltage instability, enhancing power quality. The technology also improves fault and transient event detection, allowing for better awareness of faults and providing intelligent alerting for quicker grid event responses. It can track DER performance against standards like IEEE 1547, providing valuable insights for regulatory compliance and system planning [2].

Moreover, the monitoring technology facilitates near-real-time grid event notifications, enabling early detection of faults and proactive transmission grid management. It supports aggregate DER dynamic model validation, helping assess the impact of DERs on transmission systems and improving forecasting and model accuracy. The technology also aids in dynamic load model validation, system model validation, and time synchronization across devices and systems. Additionally, it offers early warning indicators, pre-event analysis, and wide-area oscillation monitoring, contributing to enhanced grid reliability and system performance through high-resolution data and integration with other data sources [3], [4], [5].

VELCO and VEC Pilot Project

VELCO and VEC conducted a small-scale pilot deployment of the point-on-wave monitoring technology in the South Hero region of Vermont, installing 17 sensors connected to two distribution circuits. The sensors were rapidly deployed within one month, capturing near-real time data during the 2024 solar eclipse, which revealed impacts on VEC distribution system voltages and highlighted potential abnormalities like switching events, faults, and harmonics. Following this initial pilot deployment, VELCO, with funding from Oak Ridge National Laboratory (ORNL), installed 34 more sensors in October 2024 across multiple distribution

substations, all streaming data to the centralized platform within one month. This fast deployment and data accessibility is a valuable asset for grid operators. Figure 5 shows the installation locations for the initial pilot in South Hero and the additional 34 sensor deployments.

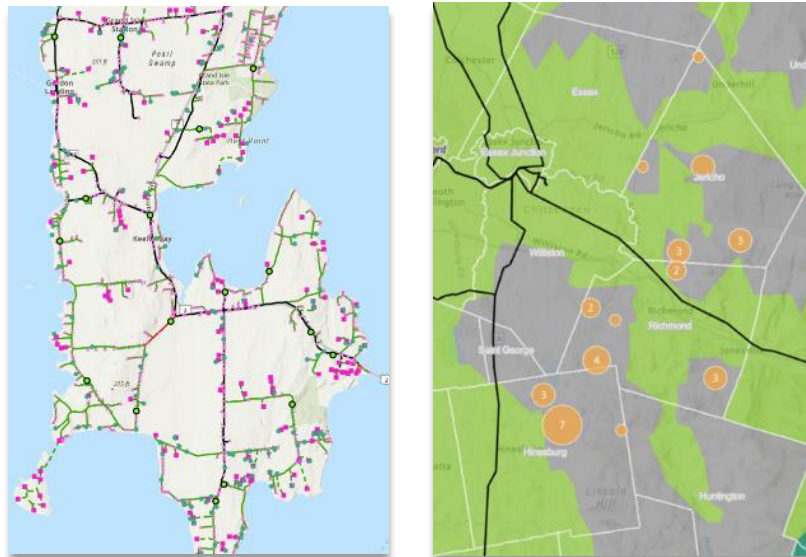


Figure 5: Point-on-Wave Monitoring Sensors in South Hero (left) and other Vermont Areas (right)

DER Penetration in the South Hero Area

The South Hero area of the VEC system has a relatively high DER penetration level relative to system demand in that area. As of November 2024, a total of 292 DERs are installed in South Hero with a total installed capacity of 7,683 kW. Figure 6 shows the DER locations in the South Hero area associated with the South Hero Substation (also known as Substation 29) across Feeder 1 (north) and Feeder 3 (south). The tables and graphs show that nearly all the installed DER capacity is solar PV generation.

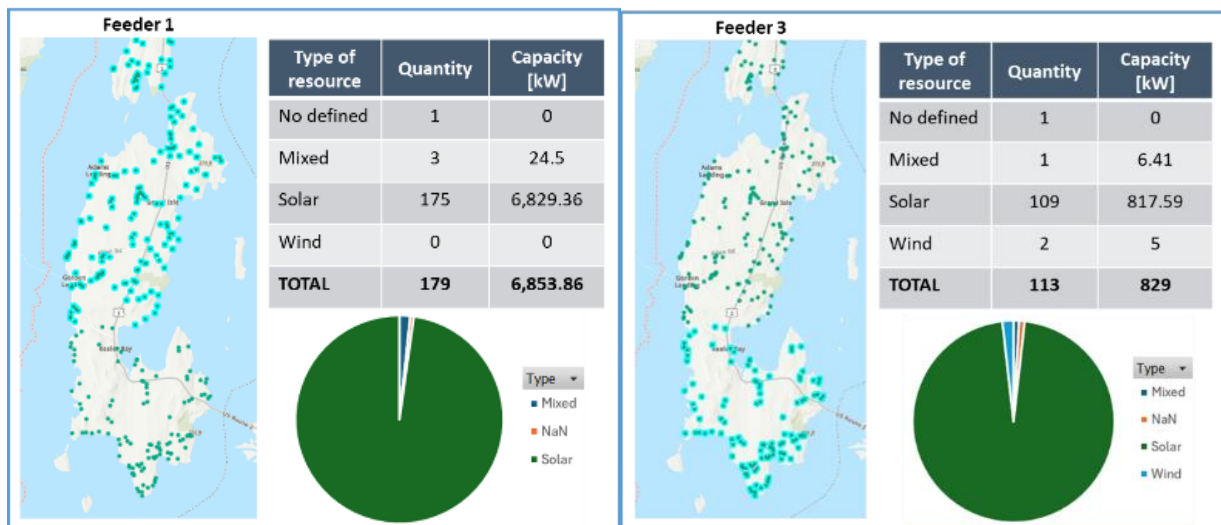


Figure 6: Location of DERs Across Feeder 1 and Feeder 3 in the South Hero Area

Deployment and Data Streaming in Vermont

In March 2024, the point-on-wave monitoring sensors were installed in 17 locations within the distribution footprint in the South Hero area. These sensors, placed at broadband provider UPSs on the distribution circuits, capture raw measurement data (such as voltage waveforms and light) and stream it over the broadband network to a server that host a centralized monitoring and analytics platform. The data is accessible via a plotter tool, which allows viewing and downloading high-resolution data in various formats, including POW data, CSV files, and COMTRADE files [6].

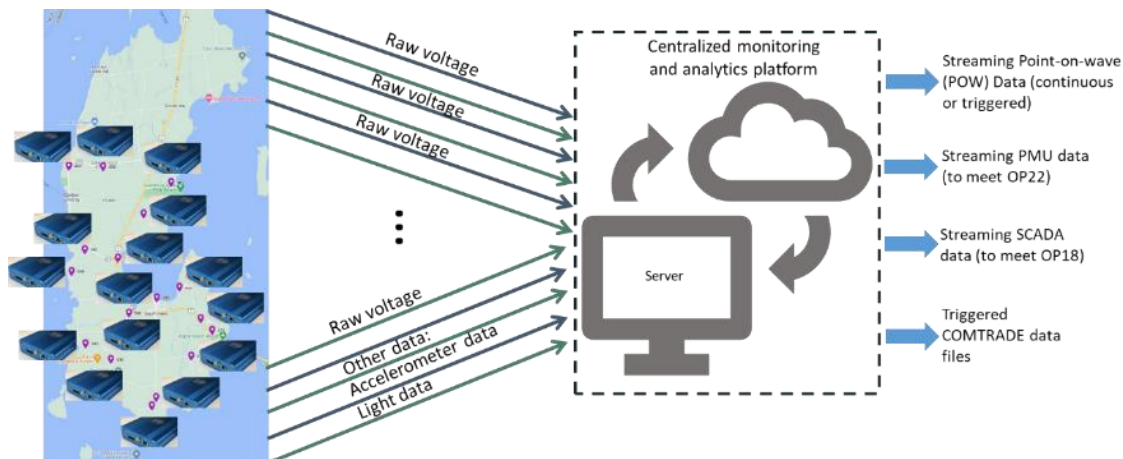


Figure 7: Configuration and Data Flow between the Monitoring Sensors and the Centralized Monitoring and Analytics Platform for South Hero Area Pilot Project

Figure 7 illustrates the installation of point-on-wave monitoring sensors in the VEC distribution system. The broadband UPS, installed on a distribution pole, powers the sensor, which captures high-speed data sampling. The sensor streams raw waveform data to the server via a modem and the broadband network. The installation process revealed no distribution outages, utility crew involvement, or additional telecommunications equipment required, demonstrating that the sensor installation could be completed without electric utility support.

Core Applications & Analysis of Grid Events

Core Applications

This section highlights four core applications identified by VELCO and VEC during the South Hero pilot project using the monitoring technology. While a detailed analysis of each application is still needed to address the specific contexts of the stakeholders involved, this summary provides key findings, recommendations, and insights into the role point-on-wave monitoring technology can play in each application.

Aggregate DER Event Analysis and Transmission Model Validation

This section discusses aggregate DER event analysis and transmission model validation critical to VELCO. VELCO requires an in-depth examination of DER performance during distribution events and its ability to meet IEEE 1547 ride-through requirements [4]. In response, an analysis framework is being developed to assess DERs in relation to grid disturbances, using characteristics such as IEEE 1547 standards to refine models for accurate transmission system validation. Transmission model validation focuses on analyzing the transient behavior of distribution circuits, DERs, and loads during disturbances, comparing this data to VELCO's transmission planning models to improve grid resilience. Additionally, the technology could provide near-real time awareness of DER events, automatically assessing ride-through curve compliance

and issuing alerts if thresholds are exceeded, offering a proactive tool for engineers to enhance system models and improve grid reliability.

Automatic Event Detection and Fault Analysis

VELCO has identified automatic event detection and fault analysis as significantly high-value applications for the transmission system. By utilizing point-on-wave monitoring data, these applications improve system reliability through accurate fault location, post-event analysis, and equipment failure detection. During the South Hero pilot project, a novel approach for fault location was developed, analyzing voltage magnitude data from sensors across the circuit. Sensors nearest to the fault show the largest voltage dips, allowing for faster fault location identification and improved response times. For example, during a lightning strike event on 8/14/2024, both VELCO's DFR data and the point-on-wave monitoring data captured the fault, with precise time synchronization between the datasets. This integration highlighted discrepancies in the DFR's time synchronization, demonstrating the utility of the point-on-wave monitoring technology in fault detection and system analysis.

Early Warning Indicators and Pre-Event Analysis

The raw data from point-on-wave monitoring provides valuable "ambient data" that can act as early warning indicators for system stress, equipment issues, and potential grid disturbances. By analyzing this high-resolution data, utilities can identify underlying conditions signaling impending issues. When combined with other data sources like PMU, SCADA, and DFR data, it enhances the analysis of system health and stress. Aggregating this data into a comprehensive archive enables system-wide analysis, improving predictive capabilities, identifying emerging risks, and supporting proactive decision-making.

System Monitoring and Improved Situational Awareness

Throughout the pilot project, VELCO and VEC also identified ancillary benefits for the distribution system in addition to all the primary transmission applications and benefits. These ancillary benefits include system monitoring for operational situational awareness. This includes several monitoring applications, such as:

- **Regulatory Electric Service Requirements:** Point-on-wave monitoring can track voltage and frequency, ensuring compliance with regulatory thresholds.
- **Power Quality and Protection:** It can detect issues like harmonics, voltage distortions, and slow-clearing faults, improving power quality and protection.
- **Verifying Phasing:** By mapping sensor data to geographic information system (GIS) data, discrepancies in voltage phase data were uncovered, helping accurately determine equipment phases and update transmission and distribution system models.
- **Integration with GIS Platforms:** Integration of the RMS voltage data from the point-on-wave monitoring sensors into the real time or near-real time GIS platforms for enhanced grid monitoring and real time operational insights, particularly concerning DER flexibility.

Fault Event Analysis

This section presents an application example that highlights the potential of the GVP tool for analyzing aggregated DER events. To evaluate the relevance of the monitoring technology data and its value for VELCO's transmission system, the project team examined various grid events captured by the data. This paper discusses key insights from two such events recorded during the project. One of the primary objectives of this analysis was to assess the voltage waveform data from the monitoring technology in the context of the IEEE 1547-2018 DER ride-through performance curves [2]. This approach aimed to better understand the severity of the voltage excursions, their potential impact on DER performance, and the ability of the technology data to support similar applications in the future.

Event 1: 4/26/2024, 1:48 PM EDT

An event was identified on April 26, 2024, at 1:48 PM EDT.

2025 Georgia Tech Fault Disturbance & Analysis Conference

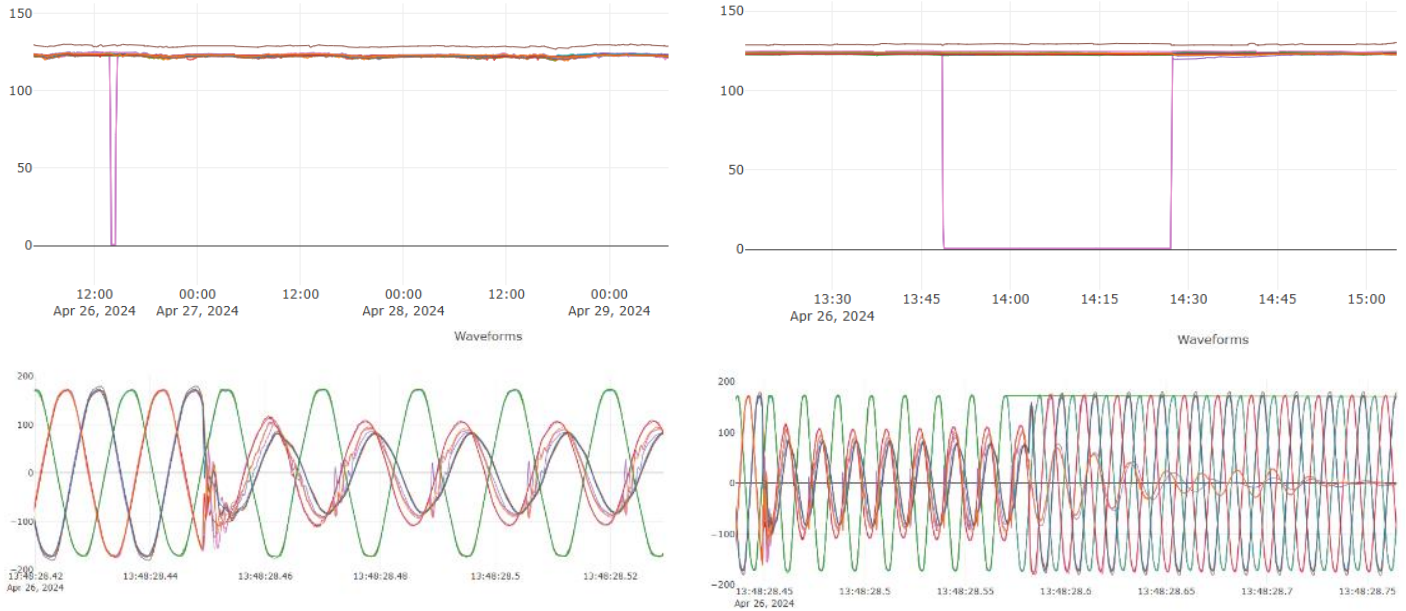


Figure 8: Voltage Data from 4/26/2024 Event. Top: Voltage RMS Plots. Bottom: Voltage POW Plots

Figure 8 and Figure 9 show the voltage dropping, approximately, to 45%, recovering back to over 90% of nominal voltage 118 milliseconds (ms) later for some sensors, and going to 0 V in 246 ms from other sensors.



Figure 9: Event 1 Voltage Waveforms of applicable Monitoring Sensors

Figure 10 presents the category 3 IEEE 1547 ride-through curves for Event 1 sensor data.

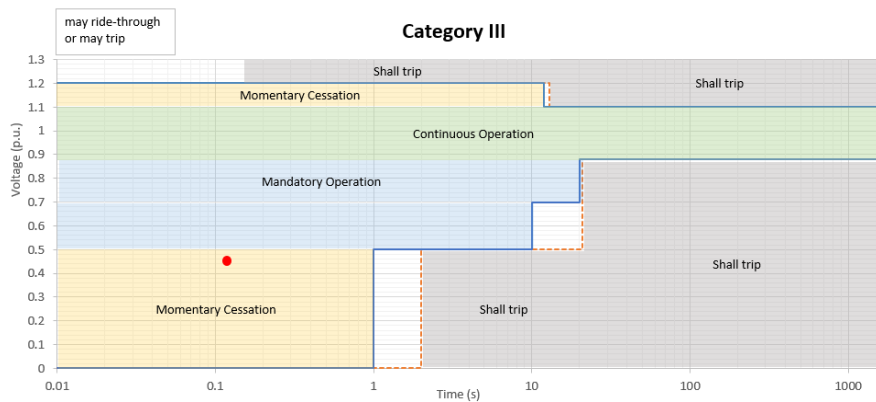


Figure 10: IEEE 1547 Ride-Through Curves for Event 1

Event 2: 8/14/2024, 10:58 PM EDT

An event was identified on August 14, 2024, at 10:58 PM EDT. The event corresponds to a lightning strike that caused a fault on the South Hero 115 kV line.

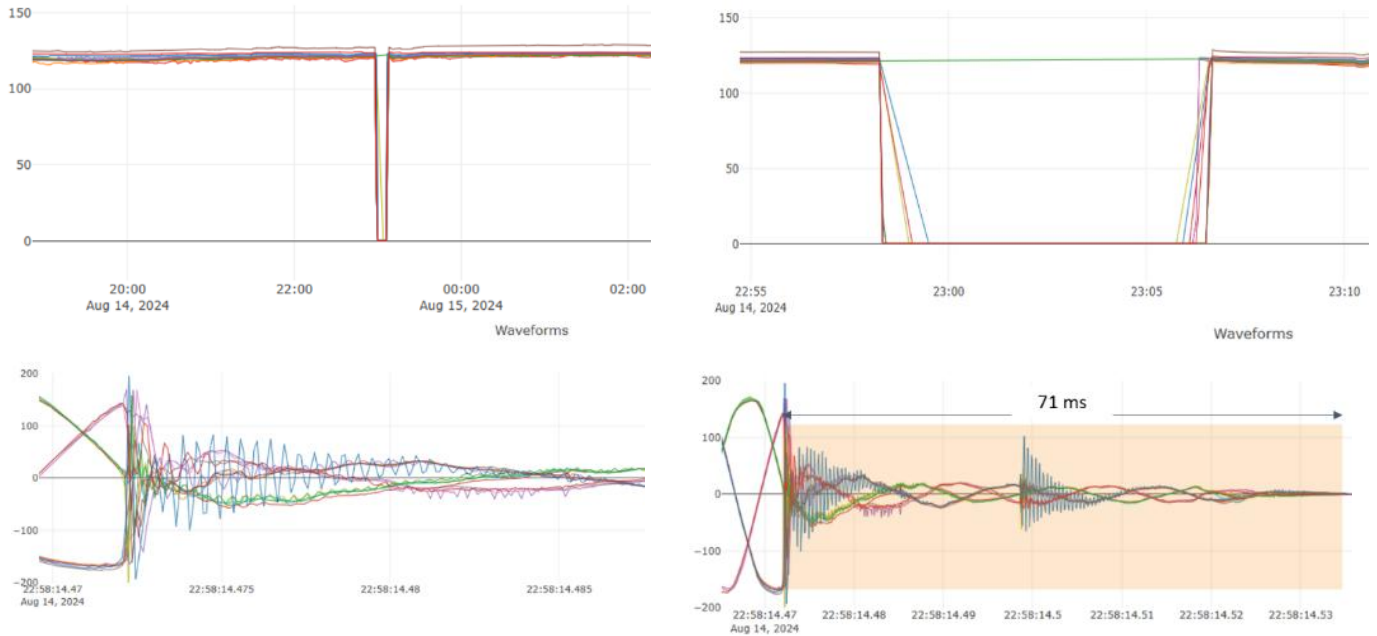


Figure 11: Voltage Data from 8/14/2024 Event. Top: Voltage RMS Plots. Bottom: Voltage POW data.

Figure 11 and Figure 12 show that the voltage is going to 0 V for all sensors in 71 ms. Figure 13 compares the voltage plots for the same event of the monitoring technology sensors and PMU data from ISO-NE.

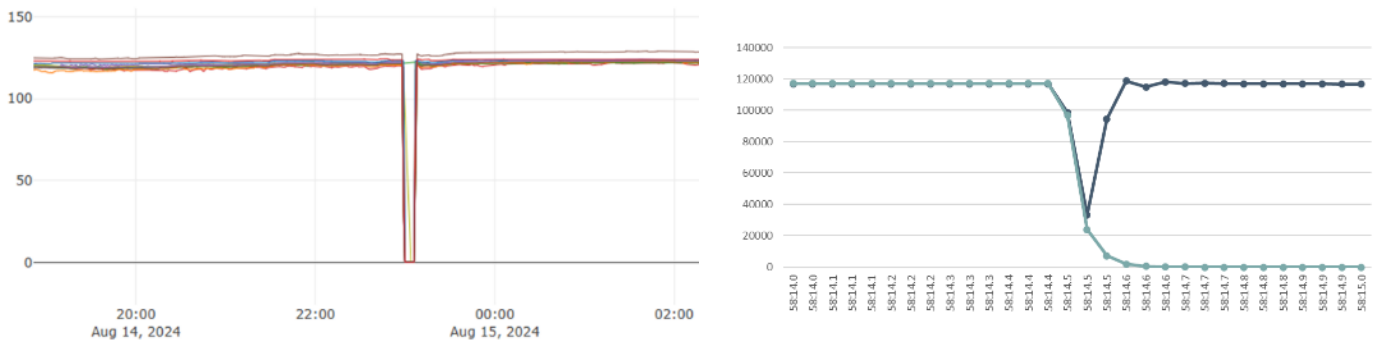


Figure 13: Event 3 Voltage Record by Monitoring Sensors (left) and PMU Data Provided by ISO-NE (right)

Note that under the IEEE 1547-2003 standard, DERs were not required to have fault ride-through capabilities. In addition, while protection settings can vary depending on the inverter, many DER installations compliant with the IEEE 1547-2003 standard were/are designed to trip during transmission system contingency faults. This lack of fault ride-through functionality may limit their ability to stay online and support grid stability during certain grid disturbances [7], [8]. This is the type of analysis that will be

required for further DER ride-through performance evaluation and DER model validation, and is made possible by the point-on-wave data.

Conclusions

In conclusion, the point-on-wave monitoring holds great promise for improving grid visibility and operational efficiency for transmission operations. An innovative technology solution enabling this type of monitoring, which historically has never been feasible, offers high-fidelity data that can bridge visibility gaps and improve decision-making. Successful deployment will require overcoming challenges in proof-of-concept, hardware design, and cybersecurity, but its potential benefits, such as rapid deployment and seamless fast grid integration, position it to significantly enhance grid operations and strengthen utility reliability and event analysis.

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