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CIGRE US National Committee
2022 Grid of the Future Symposium

DER Gateway to Support Real-Time Control and Situational Awareness in Distribution Grids

C. ABBEY[1], H. CHUANGPISHIT[1], J. BORCHERT[2], M. VAIMAN[3], M. KARPOUKHIN[3]
[1]Quanta Technology LLC, [2]Central Hudson, [3]V&R Energy
USA

SUMMARY

As the pace of integration of distributed energy resources (DER) accelerates, seamless integration of small capacity DER—typically installed behind the customer meter—represents a major barrier to high penetration of this segment of resources. This paper presents the design and testing of a low-cost gateway for integration of DER into distribution system operations. A prototype for a DER gateway was specified, designed, and developed, and was integrated via a field area network (FAN), with the vision that a gateway could eventually be installed with every small capacity DER, such that every residential or small commercial facility with DER would be enabled with monitoring and control functionality. To demonstrate the benefits, three widely deployed grid modernization applications were considered: fault location, isolation, and service restoration (FLISR); Volt - Var optimization (VVO), and DER dispatch. Measurements from the gateway are integrated to a three-phase hybrid distribution state estimator (HDSE) illustrating how DER measurements combined with existing phasor measurement units (PMUs) can enhance real-time situational awareness.

KEYWORDS

Distributed energy resources, DER dispatch, hybrid distribution state estimation, distribution management system, phasor measurement units, Volt-Var optimization.

cabbey@quanta-technology.com

INTRODUCTION

Decarbonization of the power system and decentralization of power generation in the form of distributed energy resources (DER), represent major long-term drivers that will markedly change the way power distribution systems are planned and operated. At low and modest levels of DER penetration–which can be thought of as the ratio of DER to the on and off peak loads of the distribution system—there is little impact and most or all DER can be integrated without adversely impacting the system or the need for advanced monitoring or control of the DER. However, when penetration levels on individual feeders or across service territory are high, either system improvements need to be made to accommodate these DER or distribution operations must undergo a shift from static control to dynamic control. Several research and demonstration projects have entertained new approaches [1]-[7], while standards and regulatory organizations have developed standards [8]-[10] and orders [11] to support this evolution.

Modernization of the grid represents another long-term need that has gained momentum over the past decade, where the merging of information and communication technologies (ICT) with the power system infrastructure enables advanced applications that can improve situational awareness for grid operators, improve efficiency of power delivery, and enhance or maintain the reliability and resilience of the system, [3], [4]. The additional measurement points from DER represent inputs to three-phase hybrid distribution state estimation (HDSE) as the deployment of phasor measurement units (PMUs) lag the number needed for fully observable systems [12]. These trends provide greater justification deploying, monitoring and control of DER, which will help coordinate these initiatives into an overarching strategy for evolution of distribution system operations.

This paper describes the analysis framework, design, test approaches and results of utilizing a low-cost gateway for integration of monitoring and control of DER into distribution system operations. The objective of the research was to illustrate viability of the concept using the Field Area Network (FAN), as described in [1], [2], and [4]. The contribution of this paper relates to the definition of an architecture for integration with grid modernization applications, namely fault location, isolation and service restoration (FLISR); Volt - Var optimization (VVO), and DER dispatch. Furthermore, a three-phase HDSE was also integrated in the demonstration to take advantage of the DER measurements and existing PMU measurements to improve situational awareness [13].

The paper first presents an overview of the rationale for the work and review of background research. It is followed by the description of the overall architecture and distributed control architecture investigated in the study. Then, details of the test environment and strategy for testing of the gateway with each of the grid modernization applications are provided, along with a summary of the results and specific results for DER dispatch. At the end of the paper, the authors provide a summary of the overall takeaways and conclusions.

DER GATEWAY AND REAL-TIME PLATFORM

Fig. 1 illustrates the electrical connection of small DER assets with power grid. One or multiple DER are connected off a service transformer that services those customers with DER and generally multiple other customers as well. As the decarbonization trend continues, more and more of these service transformers will connect DER in addition to the load they serve, increasing the overall percentage of DER at the feeder or substation level.

In the proposed arrangement, each of these DER communicates with an aggregation hub, which in turn communicates upstream and integrates to back-office applications through standard protocols, which include the advanced distribution management system (ADMS), DER management system (DERMS), and market operations, see Fig. 2. Alternatively, distributed control applications can reside at the level of the aggregation hub and respond in much tighter control loops. The aggregation hub provides aggregated DER measurements from DER assets equipped with the DER gateways and phasor measurements from distribution apparatus controllers equipped with PMUs. New DER assets can be integrated to the Field Message Bus (FMB) at commissioning using the DER gateway as part of standard interconnection requirements. This architecture facilitates group management of DER, irrespective of the third-party installer or whether the customer elects to sign up for the monitoring package, supporting the development of utility driven applications.

Fig. 3 shows the main components inside the proposed DER gateway cabinet, including those demonstrated in this paper, and those part of future work (listed as future or optional). Analog inputs, analog outputs and Global Positioning System (GPS) functionality are optional terminals for implementing PMU functionality of the gateway. The gateway integrates to the DER controller, typically using the MODBUS interface with pre-defined points list as defined in the interconnection standard. Upstream, data is exchanged with the aggregation hub or between DER gateway using one of the peer-to-peer (P2P) middleware specified in the OpenFMB standard [10]; data distribution service (DDS) was in the present work.

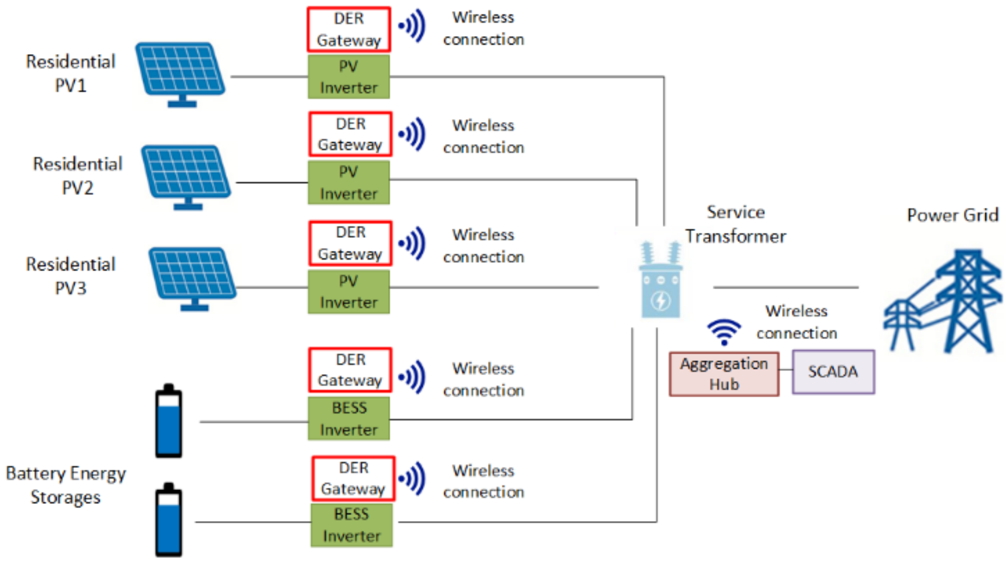

Figure. 1. Implementation of DER Gateway for Aggregation and Integration of Small DER Assets.

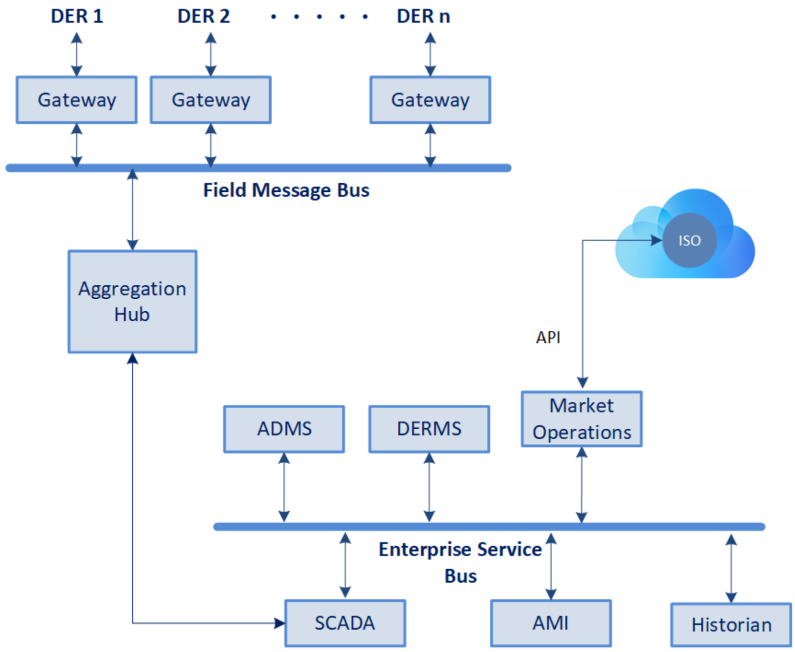

Figure 2. Distributed Control Architectures.

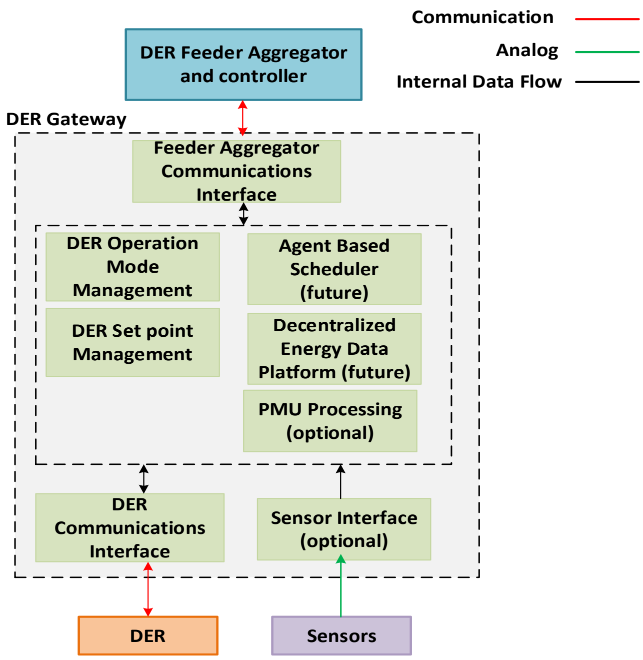

Figure 3. DER Gateway Block Diagram.

TEST ENVIRONMENT AND STRATEGY

This section describes the overall test environment used in the demonstration of the DER gateway, describing each of the subcomponents, the overall approach and objectives of the testing, and a summary of the results obtained.

Test Setup and Interfaces

Fig. 4 presents the overall set-up used in the demonstration. The set-up consists of three main components: the real-time digital simulator (RTDS) representation of the distribution system, hardware setup and interfaces between the various components of the FMB over the FAN, and the distribution state estimator. Each of the components is described together with the interfaces before proceeding to a description of the tests performed.

Three-Phase Distribution Hybrid State Estimator

Real-time distribution system monitoring is needed to account for more complex and dynamic behavior of the distribution grid with substantial penetration of renewables and inverter-based resources. To enable real-time monitoring and analysis of the distribution system, a HDSE was integrated during the demonstration to take advantage of the DER measurements and existing PMU measurements. HDSE served as a platform for testing grid modernization applications: FLISR; VVO, and DER dispatch.

There are five major inputs to HDSE, as illustrated in Fig. 5, that enable the application:

1. Streaming three-phase PMU data in IEEE Standard 37.118 at the rate of 30 samples per second.
2. Supervisory Control And Data Acquisition (SCADA) measurements, including real and reactive power injections at each bus and switch states for all breakers, reclosers, switches. SCADA data is sent to DHSE at the rate of 1 sample per second.
3. Measurements from the DER gateways. The measurements are sent to HDSE at the rate of 1 sample per second.
4. The distribution system model.
5. PMU to model mapping information.

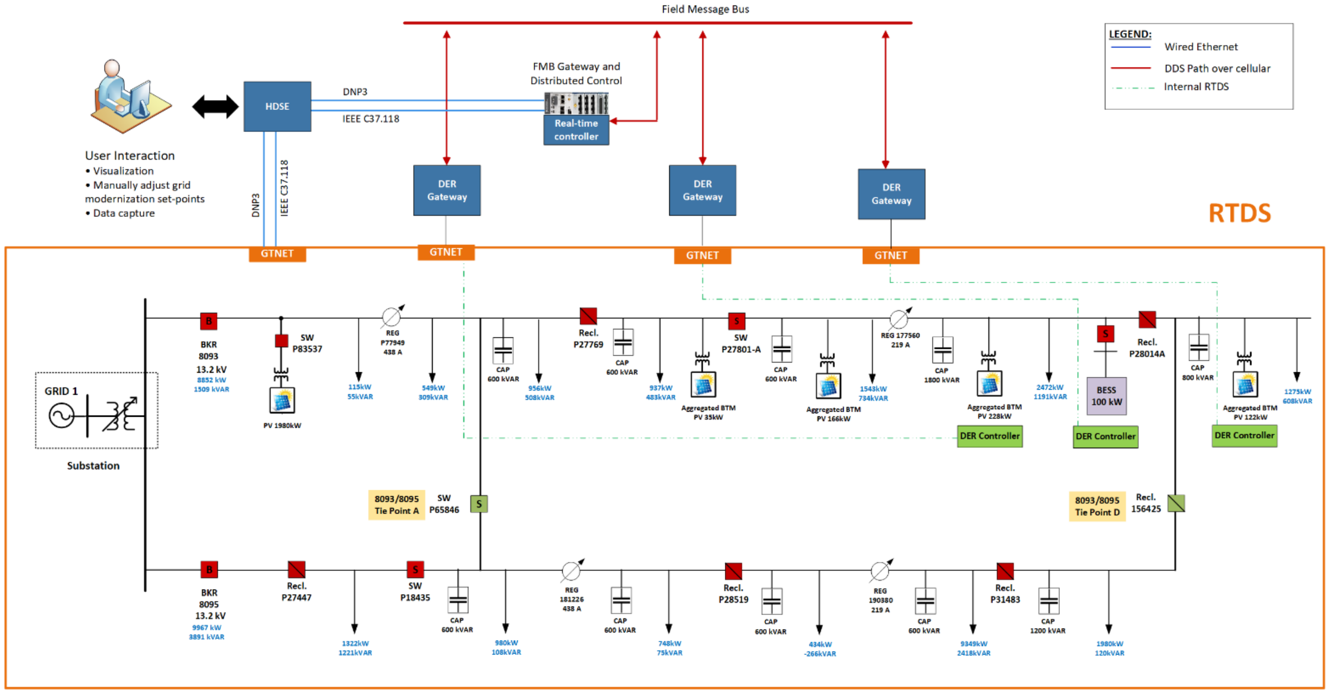

Figure 4. Real-time Test Set-up Including: Hybrid Distribution State Estimator, Field Message Bus, Aggregation Hub, DER Gateway, and Real-time Simulation.

The HDSE integrates both PMU and SCADA data and calculates the estimate of the state of the overall distribution system. The result of the HDSE is an estimate of all voltage magnitudes and angles at each bus located in the system. When presented on a graphical user interface, this provides the operator with a detailed view of the overall system and any problema or issues in an intuitive interface. This drastically improves situational awareness for the operator, and the same information can also be integrated into advanced applications to facilitate other smart grid benefits.

Though PMUs provide high-fidelity synchronized data, there are still relatively small number of PMUs installed in distribution networks and using PMU-based linear state estimation might not yet been feasible for many feeders. Therefore, using hybrid state estimation, which combines both available SCADA and PMU data is an effective transitional solution until more PMUs become available in the distribution grid. The aggregation hub (realized on Compact RIO (CRIO) hardware) outputs both active and reactive power measurements from the three DER groups located in the system. The HDSE directly integrates data from the CRIO.

The HDSE was implemented using V&R Energy's application, Distribution PMU ROSE (D-PMU ROSE), which provides real-time situational awareness to improve operation of the distribution grid and enhance its reliability. The D-PMU ROSE platform includes three-phase distribution linear, [14] and hybrid state estimation based on weighted least squares (WLS) method; bad PMU data detection and correction, [15]; observability analysis for real-time situational awareness; identification of switching events (in cases where switch statuses are not provided); archiving and alarming, advanced visualization of distribution grid; as well as optimal PMU placement for full distribution grid observability. HDSE was used as the platform to test the performance and effectiveness of the DER gateway and demonstrate the value of real-time distribution applications.

Test Cases

Load data and PV profiles were provided by Central Hudson for a substation with high penetration of DER. Three different weeks representing seasonal characteristics were selected:

- Week of January 20th, 2020
- Week of March 2nd, 2020
- Week of June 8th, 2020

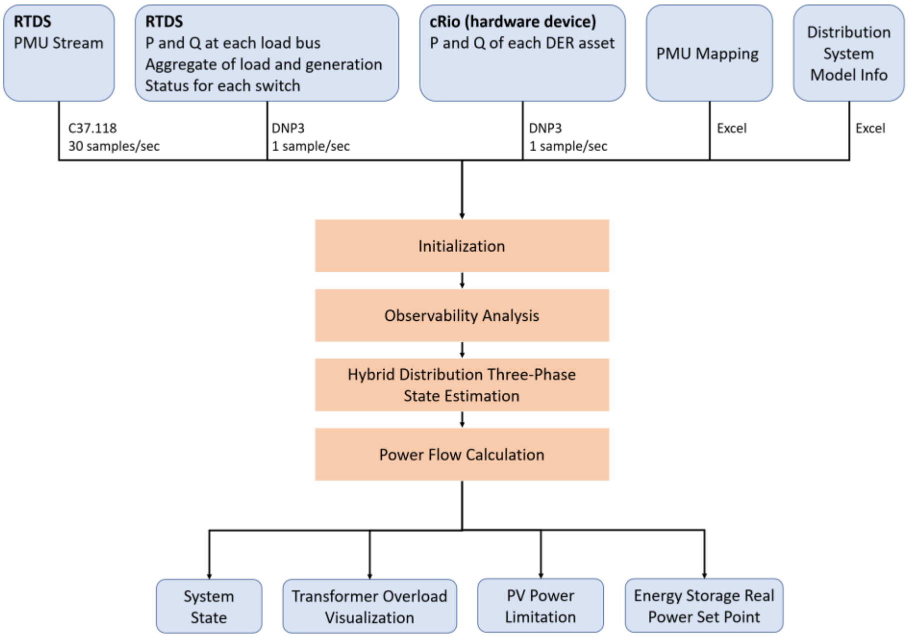

Figure 5. Distribution State Estimator Input and Outputs and Interface.

For each of the selected weeks, the load and PV profiles of a weekday and a weekend day were used for testing. This provides good sampling of the PV generation and load combinations and illustrates how the use cases will perform during different periods of the year. Fig. 6 presents a sample profile from one of the test cases, for the feeder demand and the scaled PV production (four times the actual installed PV capacity on that circuit).

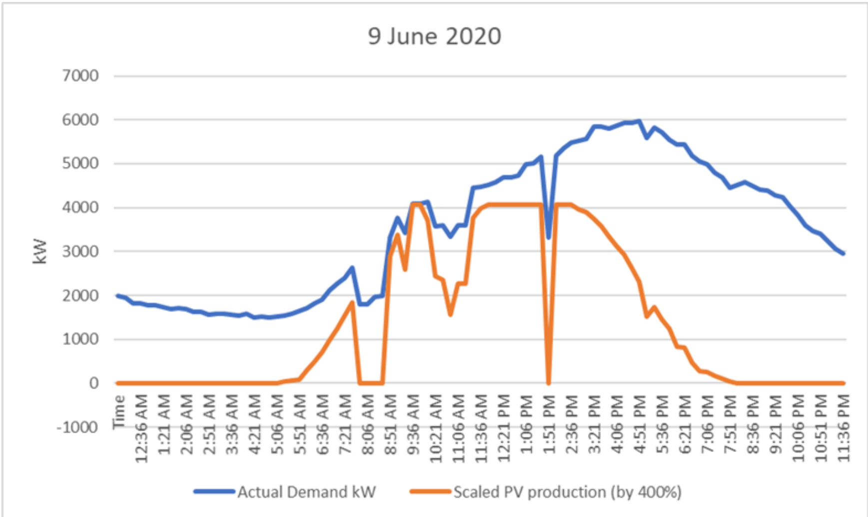

Figure 6. Feeder Loading and PV Production for Sample Test Day (June 9, 2020).

Test cases were studied for the three selected weeks, for each of the use cases. To enable quantification of the performance of the system and hence estimation of the value of the DER gateway, each test case was studied under conditions, detailed in Table I. Each grid modernization use case is compared with a baseline case with no gateway and then the same cases were run for the enhanced case, with the gateway in the loop.

Table I. Summary of Test Condition: FLISR, DER Dispatch, and VVO

Use Case	Test Sequence	Relevant KPIs
FLISR	• Fault within DER group 1 • Load sectionalized • Load in DER group 2 restored if possible	• Error in estimation of pre-fault load • % overload during restoration
DER Dispatch	• Power flow through substation monitored and back-feed conditions identified • DER dispatch to limit back-feed to zero	• Maximum recorded back-feed • Percentage of PV energy curtailed
VVO	• Voltage reduced at the substation to bring minimum voltage to lower threshold • DER groups reactive setpoints adjusted for incremental reduction	• Average incremental voltage reduction, in percentage • Min/max voltages at key buses

Results

Table II summarizes the results across the different use cases analyzed for the different test days, showing that in each case the DER gateway improves estimation of pre-fault load, reduces the back-feed condition, and provides incremental voltage reduction.

Table II. Test Results For FLISR, DER Dispatch, VVO

Test Day	FLISR	DER Dispatch		VVO
	Pre-Fault Load Estimation Error (kW)	Back-feed Base Case (kW)	Back-feed Enhanced Case (kW)	Average Incremental Voltage Reduction (%)
22-Jan-20	-	-	-	0.30%
26-Jan-20	-	-	-	0.33%
5-Mar-20	473	641	328.7	0.13%
7-Mar-20	470	376.6	38.27	0.19%
9-Jun-20	467	143.1	0	0.17%
15-Jun-20	475	406.8	230	0.12%

Figs. 7-10 illustrate the results for the DER dispatch case for a selected day (June 9). Fig. 7 shows the full day of operation (vertical red line indicates moment of DER dispatch), while Figs. 8-10 illustrate the operator view and how aggregated DER measurements enhance overall visualization, supporting better decision making when reverse power flow occurs (e.g., back-feed condition).

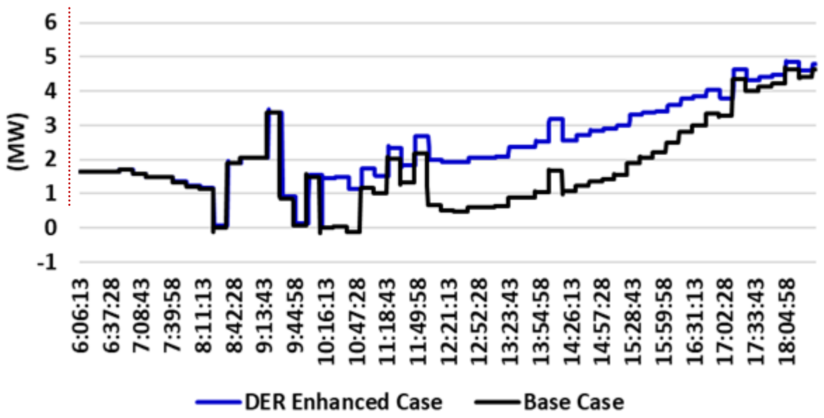

Figure 7. Active Power Measured at Breaker for DER Dispatch (June 9).

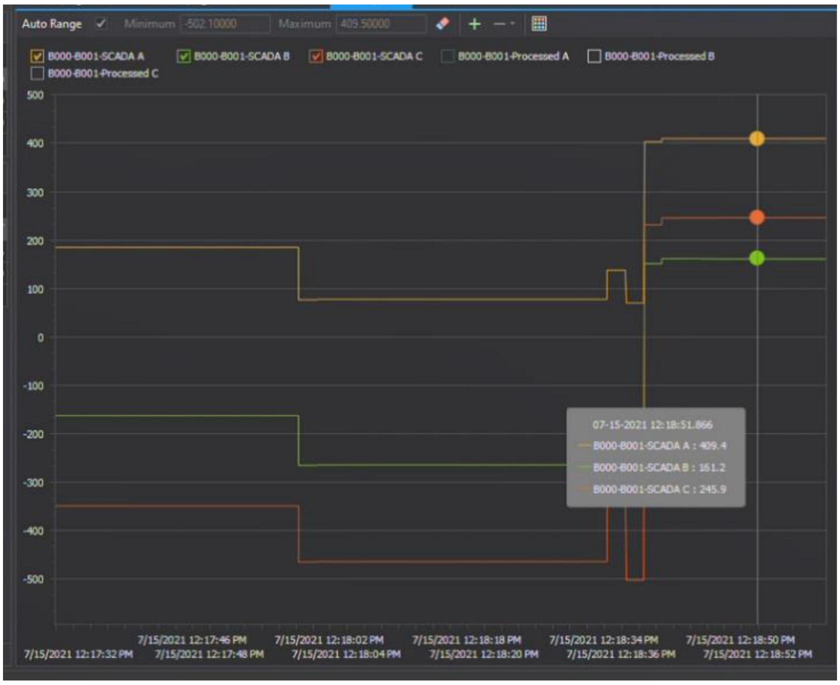

Figure 8. HDSE Real-Time Trending Visualization for Reverse Power Flow (June 9).

Groups

Name	P, kW	Q, kVAR
PVG1	806.5	0
PVG2	0	0
BESS	-99.9	0

Reclosers

Name	Current, kA	P, kW	Q, kVAR
Recl_P28014A	0.10445	623.32423	-499.94767
BRK_8093	0.3988	816.18012	-3104.00425
BRK_8095	0.593475952148438	4735.51061	-495.31060

Figure 9. HDSE Real-Time Table Visualization for Reverse Power Flow (June 9).

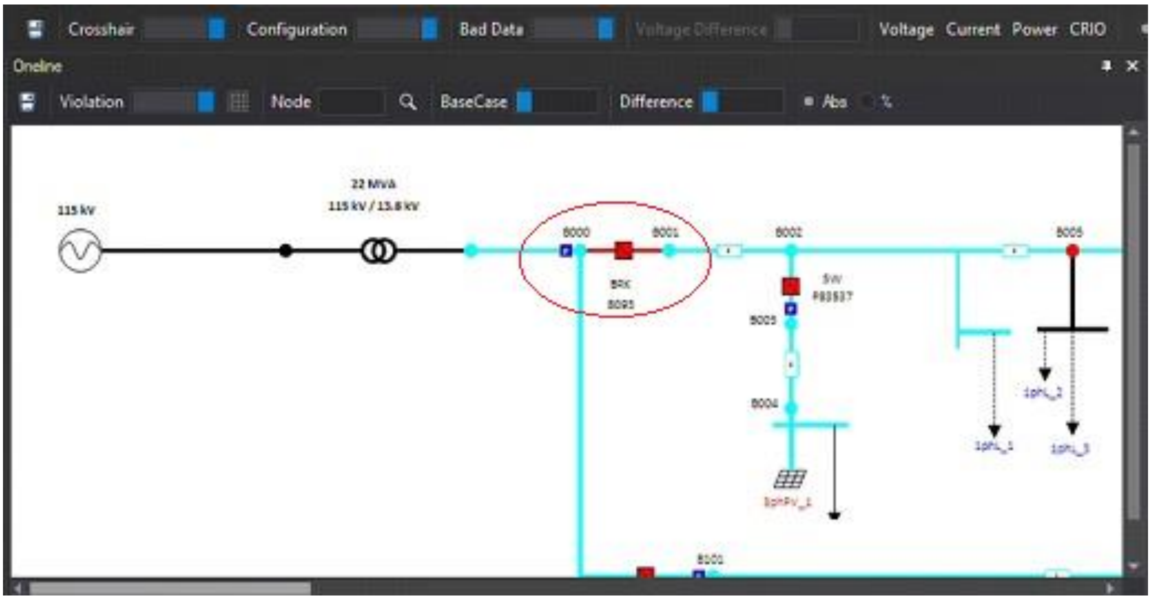

Figure 10. HDSE One-Line Real-Time Visualization Highlighting Reverse Power Flow Exceedance (Highlighted Red Feeder Breaker).

CONCLUSIONS

This paper describes research to develop a proof-of-concept of a low-cost DER gateway and presents a summary of results from the laboratory demonstration. The work led to several important insights into the role of behind-the-meter DER in supporting grid modernization applications that are currently being deployed in the industry. First, enabling monitoring and control of all DER through the gateway can positively enhance each of the three grid modernization applications studied, as well as situational awareness more generally. Given the modularity of the approach, it can be deployed in areas of greatest need rather than needing to implement something system wide, effectively building intelligence from the bottom-up. Second, the work illustrated the contribution and importance of DER measurements in hybrid DSE solution, especially in the context of few PMU measurements. Micro-PMUs embedded in the gateway would further enhance situational awareness and should be considered in future work. Finally, there is a gap in data centric distributed control applications that do not depend on model-centric view of the system. Flexible frameworks based on FMB that enable distributed decision making in the absence of underlying knowledge of system topology, but integrate with systems such as HSDE, represent a major gap to widespread use of this concept.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding from NYSERDA in support of this work and its project manager, Chris Chang, for his contributions and constructive feedback throughout the project.

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