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Grid Modernization Laboratory Consortium Southeast Regional Consortium: Technology-Driven Improvements to Power Grid Resiliency

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Sensors and Embedded Systems Group

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Recognizing that electric grid challenges can differ by geographical regions across the United States, the US Department of Energy (DOE) created a pioneer regional partnership to provide technical assistance to stakeholders facing grid modernization challenges. The southeast regional teams will transfer technologies developed under DOE sponsorship to stakeholders for testing, evaluation, and market validation. Regional members will help define critical challenges and pave the way for transitioning technologies to the commercial sector. The Southeast Regional Consortium team will use the depth of expertise at DOE's Oak Ridge National Laboratory (ORNL), Savannah River National Laboratory, the University of Tennessee's CURENT, Center for Advanced Power Energy Research, and the Clemson 20 MVA Electrical Grid Laboratory—along with critical industry partners, such as Duke Energy, Tennessee Valley Authority, Southern Company, the Electric Power Board of Chattanooga, Tennessee (EPB), and Santee Cooper. The team will conduct collaborative research to advance the state of the grid in the Southeast region and improve power system resiliency to enhance responsiveness, enable faster restoration of power, and increase distributed energy resource concentrations.

This report provides details of the technical research and demonstration projects accomplished by ORNL as part of the Southeast Regional Consortium. Specifically, ORNL analyzed impedance relays that utilize optical current and voltage measurements to assess if they could enable step distance protection to be deployed on distribution systems. This application would improve the precision of determining the geographic location of faults, increase network topology flexibility, and allow bidirectional power flow. Next, ORNL deployed time-sensitive networking technology on the EPB fiberoptic data network to study the effect of increased sensor traffic on existing supervisory control and data acquisition data. The deterministic latency and high bandwidth were demonstrated by remotely inspecting a substation using a drone with full high-definition streaming video operated at the EPB control center. Finally, a new application-based communication and control system developed at ORNL called "CSEISMIC" (Complete System-level Efficient and Interoperable Solution for Microgrid Integrated Controls) was tested for future deployment on the EPB control center microgrid using a hardware-in-the-loop test bed that was also developed at ORNL. The controller successfully optimized ancillary service when the microgrid was connected to the distribution network. The seamless islanding, resynchronization, and reconnection of the microgrid were also demonstrated through the testing.

1. INTRODUCTION

Utility companies in the Southeast United States face unique challenges compared with other geographic regions of the United States. The Southeast generation mix is experiencing a transformation driven by energy policies and low-cost shale gas, resulting in fewer coal power plants and more natural gas generation. This change has caused many coal plants to operate in load-following modes, which increases the stress on the plants, leading to higher failure rates. Along with this shift to natural gas, the increasing trend of solar generation installations can present operational challenges. Additionally, the Southeast faces many types of extreme weather conditions. This region has the highest frequency of hurricanes in the United States. From 1851 to 2010, 331 hurricanes affected the Southeast compared with 64 that struck Texas and 58 that hit the Northeast [1]. Over the same period, 93 major hurricanes made landfall in the Southeast, 19 in Texas, and 15 in the Northeast [1]. In 2011 alone, the Federal Emergency Management Agency declared federal disasters for counties in certain regions of the Southeast four times. In April 2011, nine tornados ripped through neighborhoods and business districts, affecting large swaths of the region. Ice storms also inflict significant damage to transmission and distribution lines in the Southeast, presenting reliability implications.

Under the US Department of Energy (DOE) Grid Modernization Laboratory Consortium, DOE's Oak Ridge National Laboratory (ORNL) and Savannah River National Laboratory (SRNL)—along with regional stakeholder including utilities, regulatory agencies, and universities—investigate technologies to improve distribution system resiliency. Specifically, the consortium will demonstrate the effectiveness of emerging advanced sensor, communication, and control technologies to increase distribution resiliency. During this project, SRNL and ORNL held two workshops with regional stakeholders, including the Electric Power Board of Chattanooga, Tennessee (EPB), Center for Advanced Power Energy Research, Clemson University, University of North Carolina-Charlotte, Santee Cooper, Duke University, Southern Company, DOE Office of Electricity, South Carolina Energy & Gas (SCE&G), Electric Power Research Institute, and Pacific Northwest National Laboratory. The first workshop provided stakeholder input on the expected future resiliency challenges, key technical challenges, and technology transition costs. The second workshop involved presentations by regional stakeholder and discussion topics included the following:

- Goals and objectives of the Southeast Regional Partnership
- Challenges facing the Southeast region in grid operations, renewables, and storage
- Building out the grid of the future and workforce development
- DOE's H2@Scale program
- Why workforce development must be a partnership
- Results from the Southeast Consortium technical demonstrations

The core technical task accomplished by SRNL and ORNL consisted of technical demonstrations of emerging advanced technologies for improving power grid resiliency.

This report provides details of the experimental design, execution, and results of the ORNL technical demonstrations. ORNL performed three technical demonstrations as part of the consortium in collaboration with EPB and .

The first technical demonstration showed that the application of new passive optical sensing technologies can be used to enable impedance relays for distribution systems. Unlike an overcurrent relay, impedance or distance relays have a controlled zone of protection or reach, which has the advantages of eliminating the need for a pilot channel to communicate between relays, simple time coordination between relays across the system, improved security, and avoidance of current reversals on parallel lines [2]. Impedance relays require measurements of the impedance magnitude and angle. Current impedance relays can only be used on transmission systems because their large impedance magnitudes and angles are easier to measure than the small impedance magnitudes and angles in distribution systems.

The second technical demonstration deployed time-sensitive networking (TSN) technology on unused fibers in the EPB fiberoptic data network. Underlying all the potential sensing and control techniques for improving distribution resilience is a data network required to transfer sensor readings and actuation commands across the large geographic footprint of distribution systems. More advanced central, hierarchical, decentralized, or distributed control architectures will require tight deterministic bounds on data transfer that do not exist in currently implemented network protocols. TSN provides the required time determinism.

The final technical demonstration was the implementation and testing of distributed controls for distribution system to provide resiliency increasing features such as islanding and resynching of distribution connected microgrids and the deployment of distributed storage. The distributed control architecture was implemented and tested using the ORNL Complete System-level Efficient and Interoperable Solution for Microgrid Integrated Controls (CSEISMIC). The EPB control center microgrid was used as the model system for testing the distributed microgrid controls.

The rest of this report is organized as follows. Section 2 provides details of the fabrication, testing, and results of a new type of impedance protection relay that uses new SmartSenseCom (SSC) passive optical sensors to measure the small magnitudes and angles of distribution system impedances. Section 3 discusses the deployment and testing of TSN technology on unused fiberoptic lines in EPB's fiberoptic data network. Section 4 describes the CSEISMIC test bed, EPB control center microgrid model, distributed controls implementation, and test results. Finally, Section 5 concludes the report with a summary of the technical demonstrations and how they will improve the resiliency of distribution systems in the future.

2. OPTICAL SENSING IMPEDANCE PROTECTION RELAY

2.1 OBJECTIVE

The objective of this project was to demonstrate an application of distance impedance protection using the SSC passive optical current and voltage sensor. The combined system could provide the accuracy needed for sensing and measurement of small impedance magnitude and angle in electrical distribution systems protection schemes. A few of the benefits for this application are the following:

- Only one set of three-phase current and voltage sensors needed for protection, control, metering, and power quality because of a linear response and no saturation
- High immunity to electromagnetic interference
- Accuracy and precision for sensing and measurement of small line impedance across a wide range of applications
- Small open secondary voltages that do not need shorting strips for current measurements
- Optically isolated from high voltage conductor, reducing issues with safety

2.2 BACKGROUND

The conventional design of distribution system equipment and devices somewhat limits advances in instrument transformer measurements and sensing. The majority of distribution equipment is designed and manufactured to meet standards set by the industry and limits the trial of new technologies. Three-phase protective relays and metering are designed to stringent standards based on iron core instrument transformers with various accuracy and rating classes depending on the application. These measurement and sensing devices are standardized with inputs of 1 or 5 A current inputs that can withstand as much as 1,250 A for one cycle, and voltage inputs of 600 V withstand voltage ranges from 69 to 120 V. IEC (International Electrotechnical Commission)-61850 standards attempt to provide guidelines that will allow new designs for modern power system protection and control devices and associated equipment, allowing opportunities for instrument transformer inputs as low-energy analog (LEA), high-energy analog (HEA), or digital (IEC-61850 data) signals.

New techniques for current- and voltage-sensing measurements are not easily interfaced to the standardized analog inputs for protection, control, and metering. Typical step distance relays only accept analog input of 0–5 A or 0–1 A current and 0–120 V or 0–67 V voltage, based on American National Standards Institute (ANSI) relay class iron core or window type instrument transformers. The accuracy and precision of the impedance element settings are limited by these instrument transformers and their associated saturation characteristics.

The inherent design of SSC optical sensors for current and voltage measurement are not limited by the typical saturation characteristics of instrument transformers. Without these limiting factors, accuracy and security can be achieved with high-precision sensing measurements for low voltage and current. This accuracy will enable impedance protection sensing for smaller magnitudes and angles seen in distribution systems. For phasor measurement unit (PMU) devices to be adopted and applied at distribution voltage levels, instrumentation for current and voltage measurement and sensing require more linear characteristics than currently provided by typical iron core instrument transformers.

The inherent saturation characteristics for conventional iron core current instrument transformers (CTs) and voltage instrument (potential) transformers (PTs) significantly affect accuracy when applying PMU technology. A wide bandwidth, secure, accurate instrument transformer will benefit the many devices and systems in a distribution when integrated with PMU functionality. A few areas that would benefit from this new measurement technique are protection and control, supervisory control and data acquisition (SCADA), energy management systems, outage management systems, distribution management systems, and revenue metering. Many other devices in modern electric distribution systems can benefit from incorporation of optical sensing technologies as shown in the following list.

- Distribution substation
- Load tap changers
- Line reclosers
- Energy management systems
- Feeder circuit and substation relay protection
- Capacitor banks
- SCADA systems
- Outage management systems
- Communications
- Voltage regulators
- Sectionalizing switchgear
- Controls
- Fault current limiters
- Distribution management systems
- Energy storage systems
- Automation
- Circuit breaker controls
- Revenue meters
- Distributed generation

There are several types of commercial power system instrument transformers, saturable magnetic core CTs, Rogowski Coil currents, closed-loop Hall Effect sensors, wound magnetic core PTs, coupling capacitor voltage transformers (CCVTs), electro-optical voltage transformers (EOVTs), and magneto-optical CTs (MOCTs) [3]. Optical instrument transformers typically have output for LEA, HEA, and digital (i.e., IEC-61850) signals. A comparison of different current and voltage sensor characteristics are shown in Table 1, Table 2**Error! Reference source not found.**, and Table 3**Error! Reference source not found.**.

Table 1. Current sensing characteristics comparison.

Characteristic	CTs	Rogowski Coil	MOCTs
Metering	Metering and Protection require different accuracy class CTs	Only one CT needed for both protection and metering	Only one CT needed for both protection and metering. The accuracy of MOCTs has been questioned on being sufficient for power systems use.
Saturation	For symmetric currents, saturation starts near 20 times rated current and rated burden. For Asymmetric currents, saturation can start at several times rated current depending on the primary system X/R value	Linear, does not Saturate	Linear, does not Saturate
High Frequency	Up to 50 kHz	Up to 1 MHz or greater	Up to 1 MHz or greater
Remanence	Remanence is possible	No remanence (No iron Core)	No remanence (No iron Core)
Secondary Winding	Requires heavy gauge conductors with shorting terminal blocks	Shielded twisted pair cable with connectors, no shorting blocks required	Shielded twisted pair cable with connectors, no shorting blocks required
Size and Weight	Large and heavy	Small and lightweight	Medium size and lightweight
Different Protection Schemes	Several CTs with different voltage/current characteristics may be required to cover multiple protection schemes	One Rogowski coil can be used for multiple protection schemes	One Rogowski coil can be used for multiple protection schemes
Personnel Safety	Open secondary can generate dangerous voltages	Safe, open secondary voltages are small	Safe, open secondary voltages are small
The impact on Environment	Oil insulated CTs can leak and rupture, sulfur hexafluoride insulated CTs can leak gas	Environmentally friendly and safe, no oil or gas	Environmentally friendly and safe, no oil or gas
Coil Resonance	No issues	Considered in design	No issues

To increase the use of many of the new technologies for instrument transformers, many of the devices themselves need new front-end input signal conversion systems and connector systems to accept the smaller input signal levels versus direct secondary voltage and current analog inputs.

Table 2. Current sensing characteristics comparison.

Characteristic	CTs	Rogowski Coil	MOCTs
Output variation with temperature	Low	Very low	Temperature- and stress-induced linear birefringence in sensing material causes error and instability
Integrator Implementation	No integrator circuitry	Digital integrator removes roadblock for more widely adoption in distribution energy meters	None
Low frequency noise magnification	No issues	Must be specifically designed to avoid this	No issues
Interference and shielding	Depends on accuracy class	Shielding low frequency magnetic field is difficult; it requires thick shielding or high permeability material	High immunity to electromagnetic interference
Conductor position sensitivity	No issues	Considered in design	Considered in design
Cost	Medium	Low	High
High Current measuring capability	Good	Very good	In the case of high current, the sensors are usually limited to measurements between 0° and 360° to avoid rotation angle ambiguities

Updating the signal acquisition for legacy systems is challenging because the majority of legacy systems are designed with specific inputs, accuracy class analog currents, and voltage from traditional iron core CTs and PTs. Typical distribution systems have very small voltage angles and discrimination of impedance and voltage is often difficult for these systems during system faults and other events. Further research and development of these high-resolution, accurate, wide-bandwidth voltage and current measurements can provide sensing not currently possible because of the small conductor angles and extremely small reactance of distribution and microgrid overhead and underground conductors. In other protective functions, advanced sensors with a linear characteristic can remove the need for complicated differential slope restraint, compensation, and harmonic filtering circuitry as required in state-of-the-art differential restraint–based protective relays.

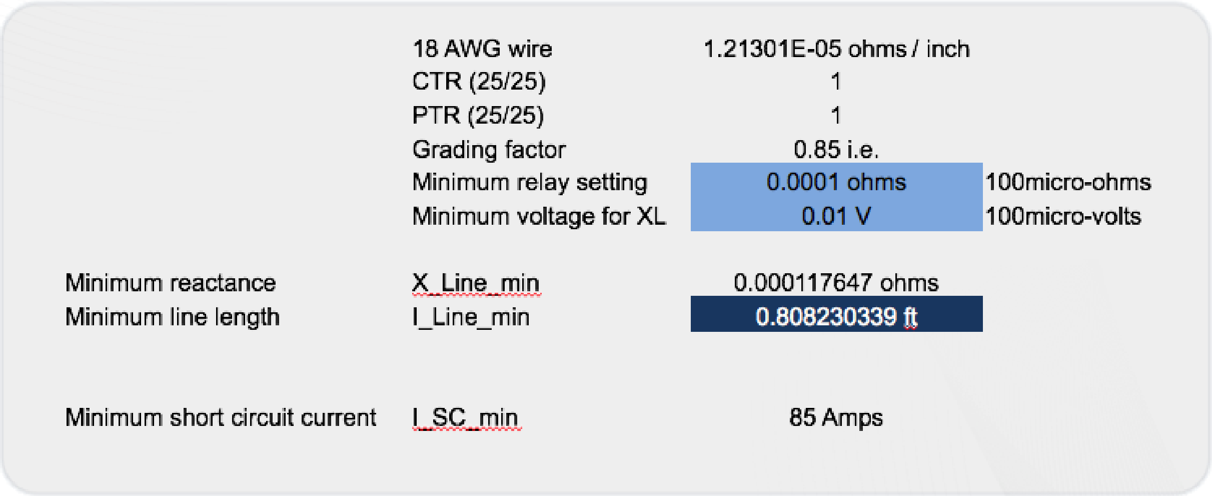
Table 3. Voltage sensing characteristics comparison.

Characteristic	PTs	CCVTs	EOVTs
Metering	Metering and Protection require different accuracy class PTs	CCVT are typically only used for protection	Only one PT needed for both protection and metering. The accuracy of EOVT has been question on being sufficient for power systems use
High frequency	Up to 50kHz	Up to 1MHz or greater	Up to 1MHz or greater
Secondary winding	Requires heavy gauge conductors	Requires heavy gauge conductors	Shielded twisted pair cable with connectors
Size and weight	Large and heavy	Medium and heavy	Medium size and lightweight
The impact on environment	Oil insulated PT can leak and rupture, SF6 insulated PT can leak gas	Environmentally friendly and safe, typically no oil or gas	Environmentally friendly and safe, no oil or gas
Output variation with temperature	Low	Low	Temperature and stress induced linear birefringence in sensing material causes error and instability
Interference and shielding	Depends on accuracy class	Shielding low frequency magnetic field is difficult; it requires thick shielding or high permeability material	High immunity to electromagnetic interference
Conductor position sensitivity	No issues	Considered in design	Considered in design
Cost	Medium	Medium	High
High voltage measuring capability	Good	Very good	Many interesting ideas for optical current sensing may be found in literature, but many are not designed for high voltage and/or high current sensing operations. However, specific applications for high current and high voltage can be found.

The motivation by customers for reliability, continuity in service and utilities for reliability, system security, selectivity, speed, and safety can be used as justification for more research in this area of sensing. Data and data accuracy can improve and accelerate many of the goals for a more intelligent grid and provide more visibility and control in more locations of modern distribution systems. The majority of distribution equipment is designed to meet industry standards, which limits adoption and testing of new technologies. A protection relay phasor measurement system can be no better than its least accurate element, and the characteristics of optical measurement technology lend to possible improvements in this area.

Distribution circuits with large amount of distributed generation or advanced microgrid power systems are defined as a conventional distribution system with interconnected distribution resources in which this added generation could carry all or a substantial portion of the islanded systems load.

Protection systems must react to the short circuit contributions during fault events while also avoiding saturation of instrument transformers, therefore requiring measurement and sensing systems that can provide sub-cycle or millisecond resolution phasor quantities. Preliminary calculations demonstrated the possibility of impedance protection for a very short section of wire (Figure 1). A general comparison of line impedance magnitude and angle is shown in Figure 2 for transmission and distribution on an R-X impedance plane.



	18 AWG wire	1.21301E-05 ohms / inch	
	CTR (25/25)	1	
	PTR (25/25)	1	
	Grading factor	0.85 i.e.	
	Minimum relay setting	0.0001 ohms	100micro-ohms
	Minimum voltage for XL	0.01 V	100micro-volts
Minimum reactance	X_Line_min	0.000117647 ohms	
Minimum line length	l_Line_min	0.808230339 ft	
Minimum short circuit current	I_SC_min	85 Amps	

Figure 1. Distance characteristics with minimum 10 mV resolution.

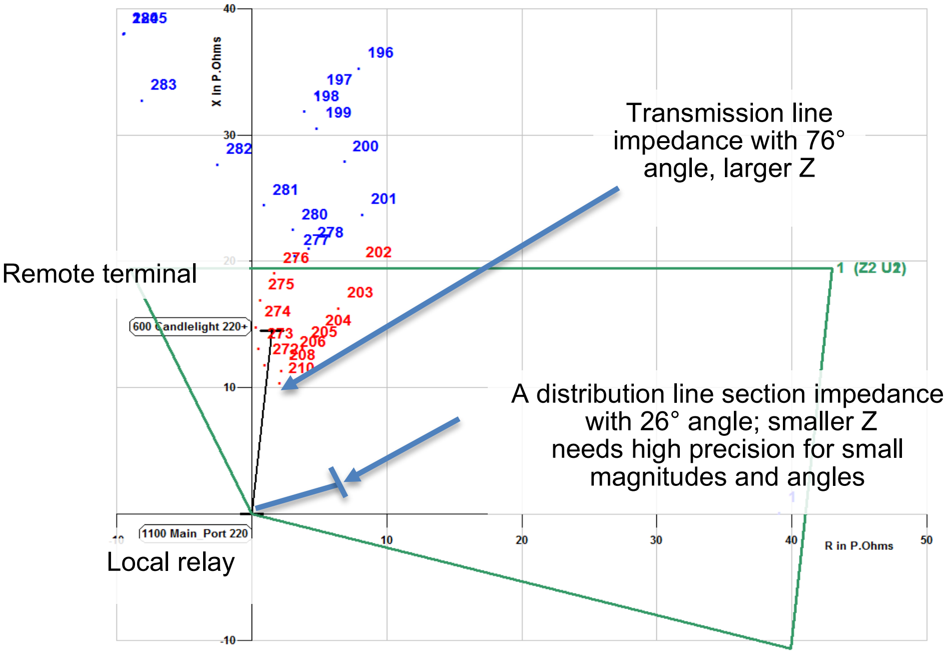


Figure 2. Comparison of transmission and distribution impedance.

The SSC vibration and acoustic system is based on an intensity modulated LED optical system, which is based on technology developed at the US Naval Research Laboratory. The system provides 24-bit, high–sample rate data with a 108 dB dynamic range above noise. This provides the basis for a platform of extreme discrimination in most environments for frequency and magnitude measurements in vibrations and acoustic signals shown in Figure 3.

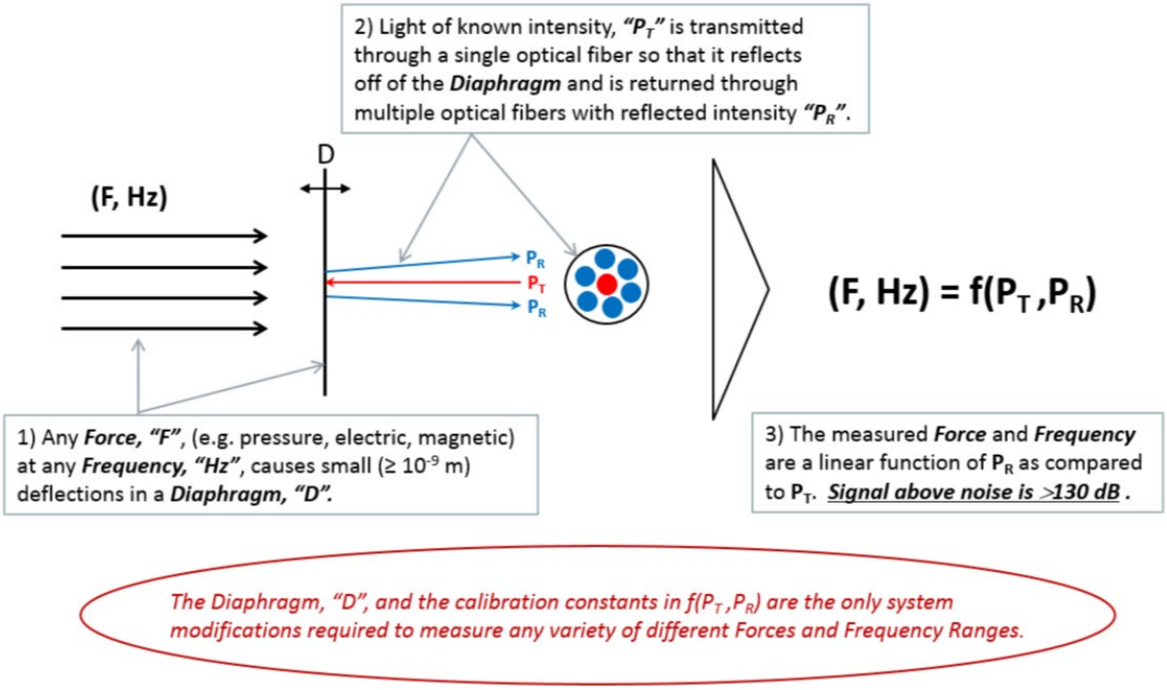


Figure 3. SSC technology overview.

2.3 PRELIMINARY OPTICAL SENSOR TESTING

The SSC 24 V, 30 A electrical phenomena cluster (EPC) sensor test was performed to demonstrate the characteristics of the sensor to be interfaced with the hardware relay controller (Figure 4). The sensor voltage and current test results are shown in Figure 5 and Figure 6.

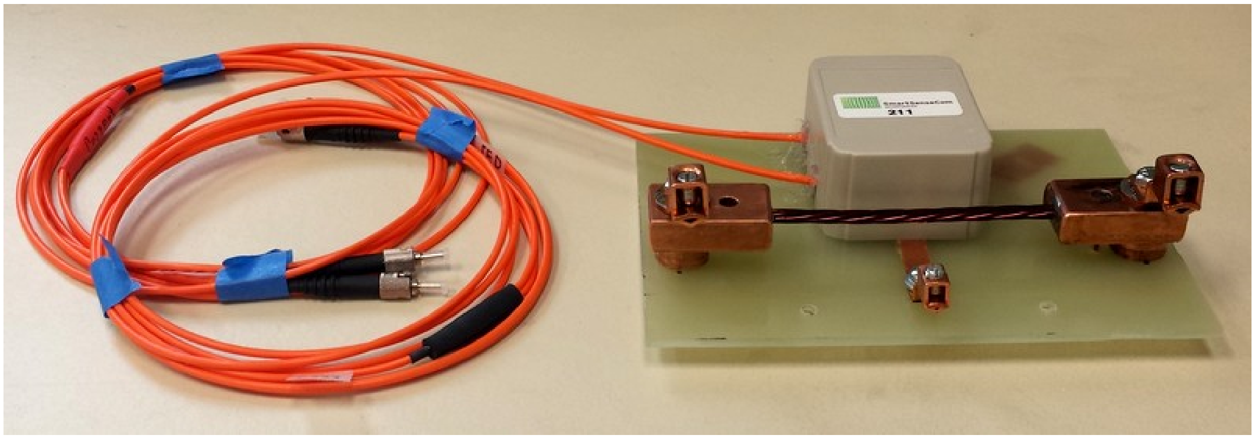
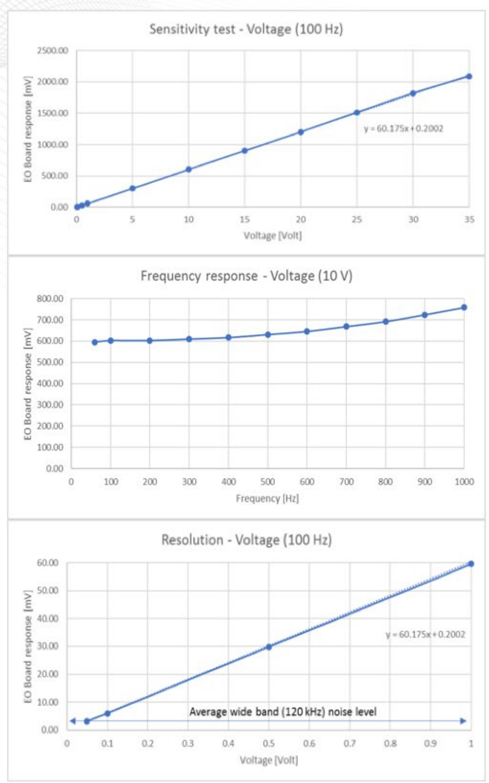


Figure 4. ORNL 24 V, 30 A EPC current and voltage SSC sensor.



Nominal voltage	24 V
Nominal current	30 A
Frequency range	60 Hz – 1 kHz
Sensitivity (voltage)	60 mV/V
Sensitivity (current)	52 mV/A
Resolution (voltage)	50 mV
Resolution (current)	60 mA

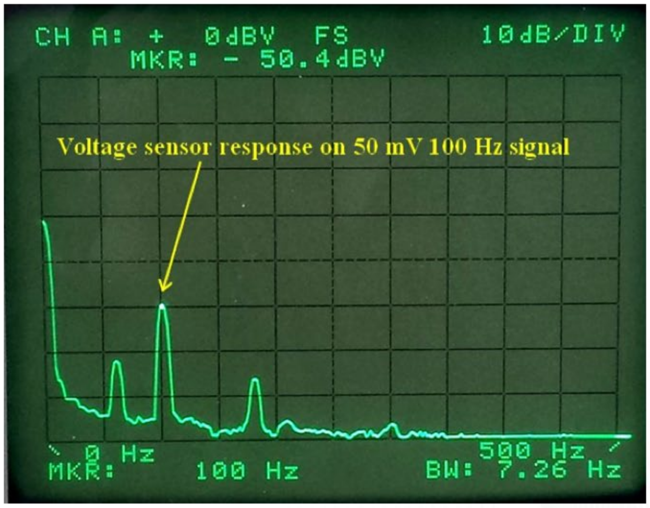
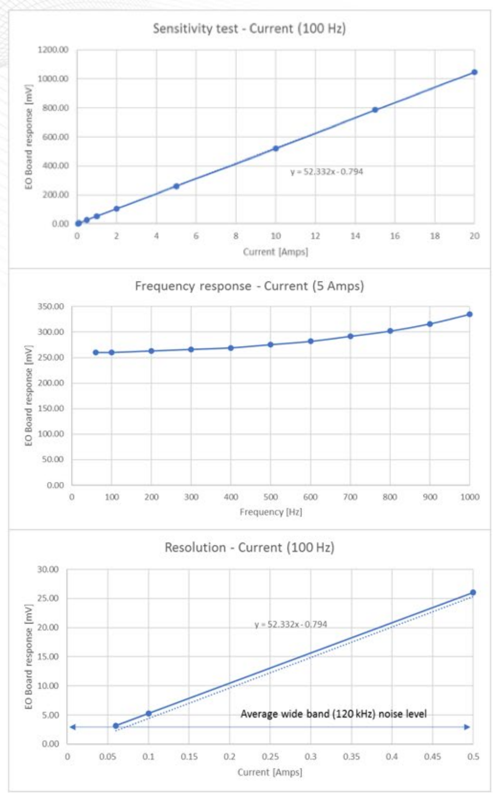


Figure 5. Voltage sensor test results.



Nominal voltage	24 V
Nominal current	30 A
Frequency range	60 Hz – 1 kHz
Sensitivity (voltage)	60 mV/V
Sensitivity (current)	52 mV/A
Resolution (voltage)	50 mV
Resolution (current)	60 mA

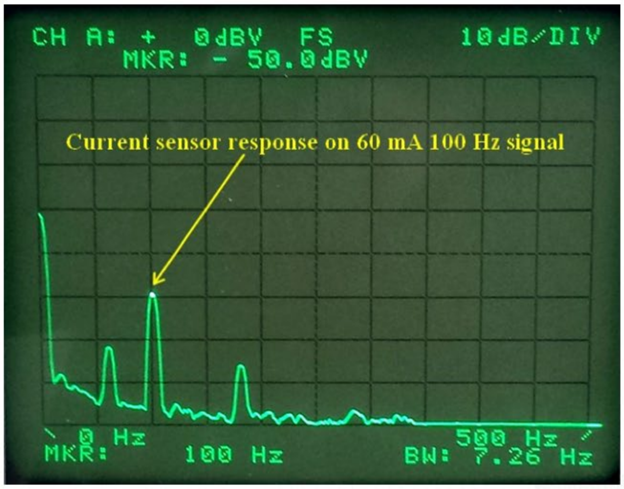


Figure 6. Current sensor test results.

2.4 HARDWARE RELAY CONTROLLER DEVELOPMENT

The impedance relay functions to be used in NI-cRIO field-programmable gate array hardware was developed and tested using MATLAB/Simulink as the simulation platform. This model will be compiled through use of the OPAL-RT solver within NI-Labview and the MATLAB solver compiler. Once this impedance relay model is linked to the hardware SSC optical current and voltage sensors through the SSC controller hardware interface, this relay model will be further tested with Doble test sources and the ORNL SI-GRID (Software-defined Intelligent Grid Research Integration and Development platform) microgrid. Figure 7 through Figure 11 show the internals of the impedance relay and initial MATLAB/Simulink fault simulation.

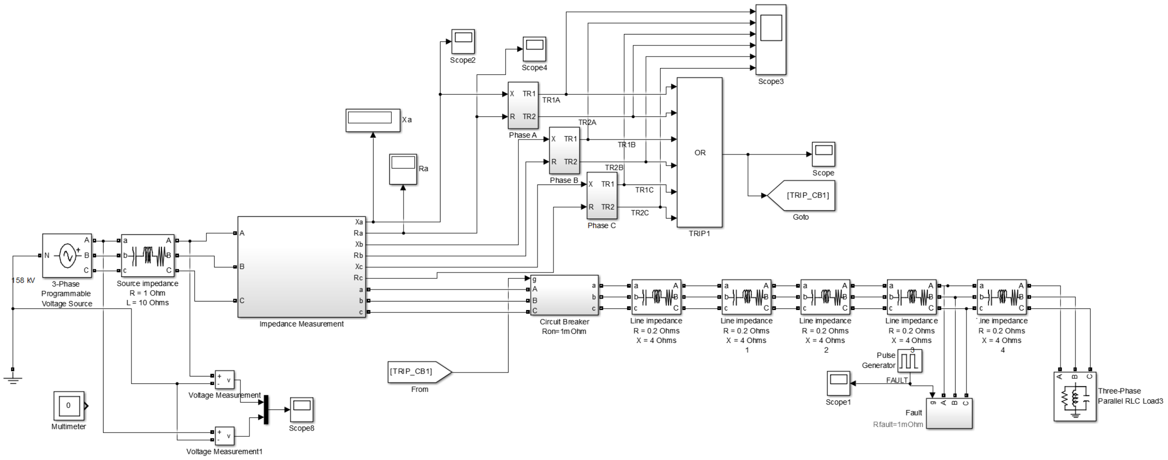


Figure 7. Power system model with relay impedance measurement.

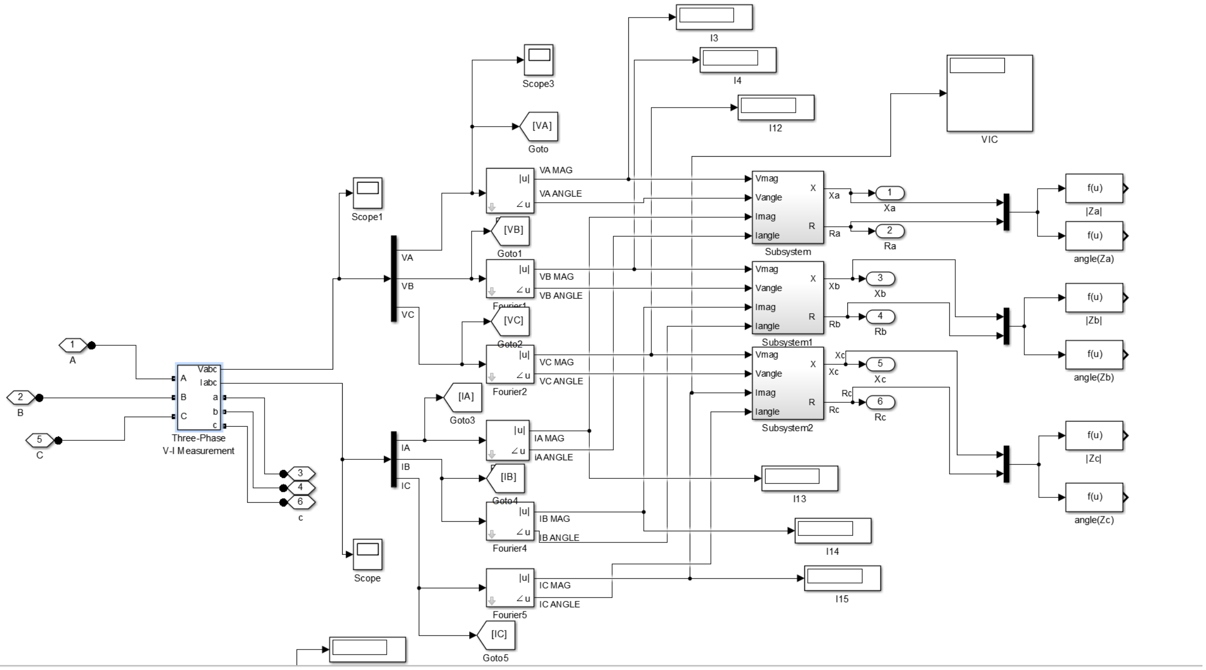


Figure 8. Internals relay voltage, current signal processing, and impedance measurement.

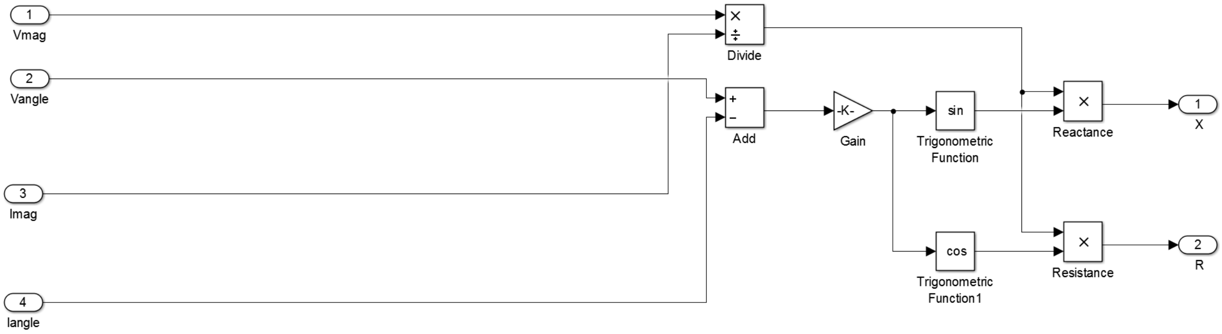


Figure 9. Internals impedance measurement for R-X.

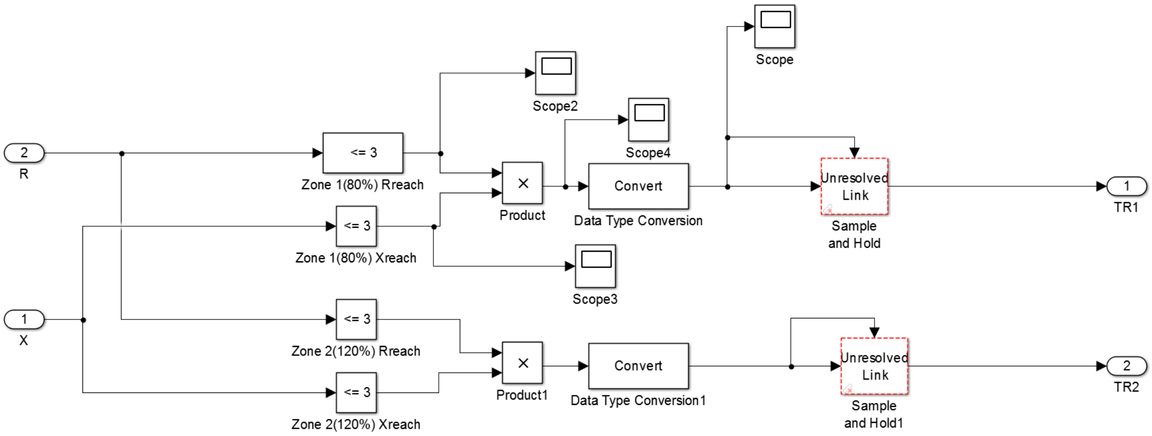


Figure 10. Internals relay impedance characteristics 2-zone reach settings.

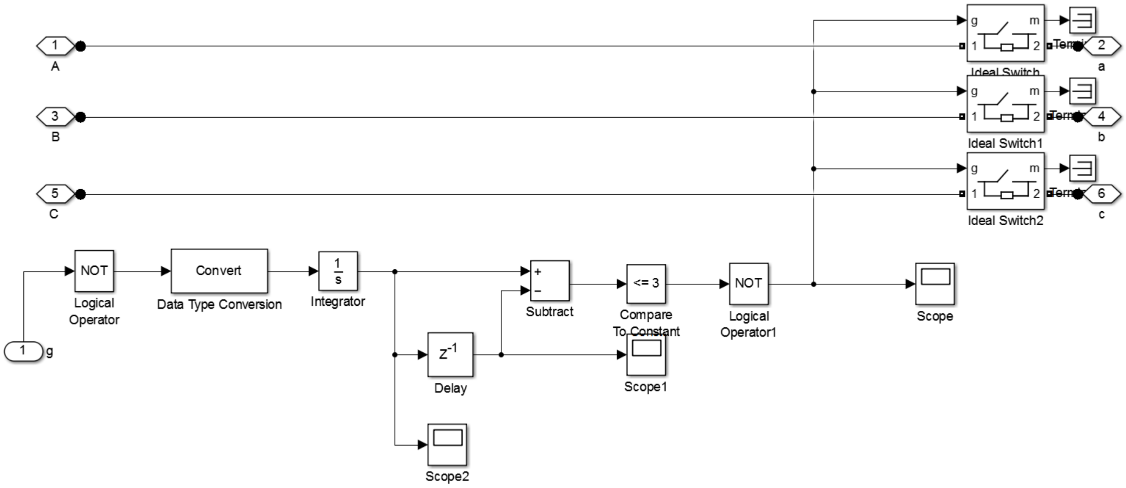


Figure 11. Internals circuit breaker.

2.5 TEST SOURCES AND TESTING PLAN

The integrated SSC sensor and NI-cRIO protection relay controller will be tested for functionality with the ORNL Distributed Energy Communications and Control (DECC) Laboratory Doble test sources, shown in Figure 12. The Doble Protest and Protection Suite software will be used to test the impedance relay functions similar to those of commercial impedance relays.

Figure 12. ORNL DECC Laboratory Doble relay test sources.

The integrated SSC sensor and NI-cRIO protection relay controller will then be tested for functionality in the ORNL SI-GRID microgrid to test the developed relay in a per-unit scaled power system to evaluate selectivity, sensitivity, reliability, and security of the protection scheme in a physical power system environment. After this testing, the goal will be to deploy and further test this system in a medium voltage distribution environment in partnership with EPB.

Figure 13. ORNL SI-GRID microgrid power systems test platform.

2.6 CONCLUSIONS

The hardware model of an impedance relay was developed in MATLAB/Simulink and will be compiled to the NI-cRIO-9039 for testing the relay and sensor system using the Doble and SI-GRID. Once these tests are completed and the results have been thoroughly examined, the next phase will be to look at funding opportunities to assist in testing on a medium voltage feeder with EPB.

This protection hardware system offers opportunities for testing other sensors that might not be compatible with standardized commercial protection relays with analog voltage and current measurement input interfaces. As show in Figure 14, SSC has developed medium voltage sensors that can speed up the process of testing this impedance protection hardware on a medium voltage system for further evaluation.

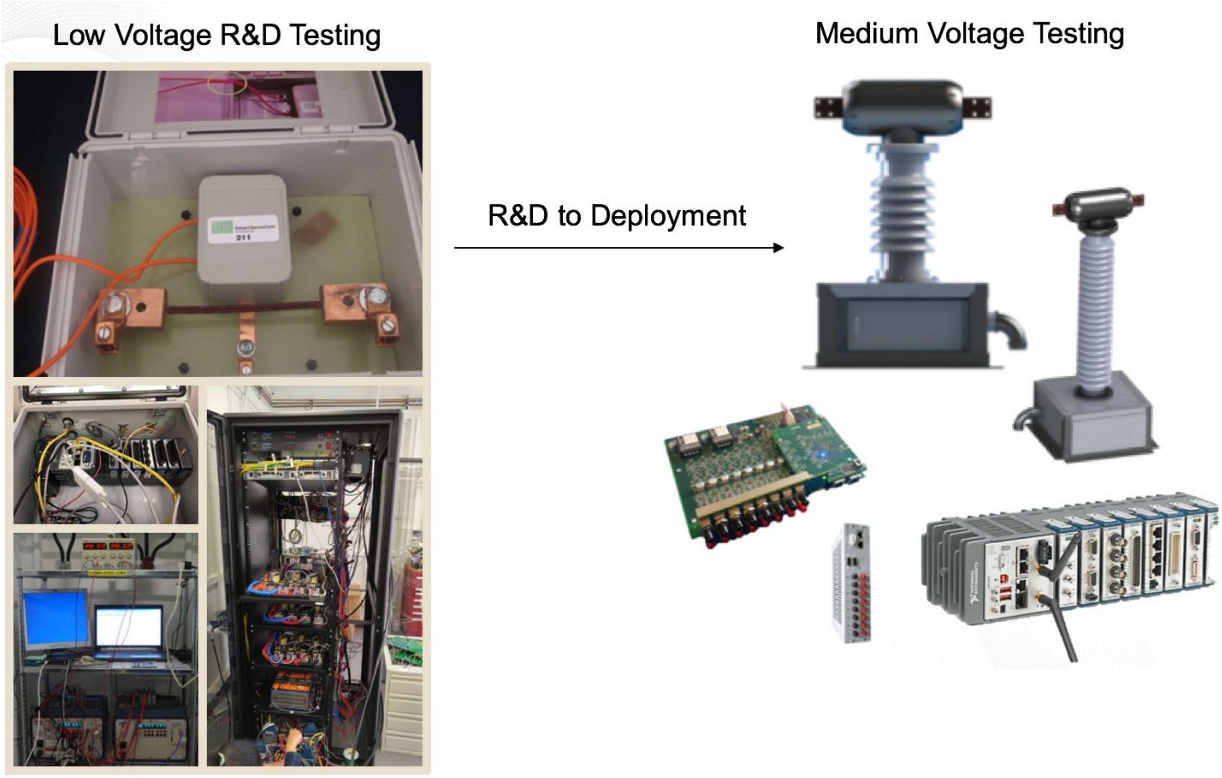


Figure 14. R&D to deployment testing.

3. TSN TESTS

3.1 INTRODUCTION

Currently, the power grid in the United States relies heavily on small numbers of bulk power generators, which makes the grid vulnerable to attacks, weather, and equipment failure because a single failure will affect the entire grid. By moving to small localized generation and storage distributed throughout the power grid, the grid will be more resilient to attacks or failures because a localized failure of a smaller distributed resource will have a proportionally small localized effect on the grid. However, creating a more resilient power grid with localized generation and storage requires that those resources be coordinated to maintain grid voltage and frequency at their nominal values and respond to changing conditions and severe weather events. The controllers that coordinate these resources will be required to send and receive data over large geographical distances, which will introduce time delays in data transmission and uncertainty in the data transmission times. Additionally, the controllers required to coordinate all these resources will need to have high performance with tight constraints on their execution time. Current public and utility data networks use network protocols, such as transmission control protocol/internet protocol (TCP/IP) over Ethernet, that do not provide low-latency data transmission with deterministic data transfer time required for high-performance distributed feedback control. TSN was designed as an extension of the Institute of Electrical and Electronics Engineers (IEEE) 802.1 data transmission protocol specifically to address latency and deterministic upper bounds on transmission time. TSN was originally developed with audio/video streaming and real-time control in automotive or industrial automation applications. The features of low latency and nonnegotiable upper bounds on end-to-end transmission latencies make TSN an excellent candidate for power grid automation. In addition to automation, TSN can provide a communications architecture for better situational awareness of the power grid, and remote operation of inspection equipment such as drones.

3.2 TSN OVERVIEW

The IEEE 802.1 working group has a TSN task group developing a set of standards to define protocols for time-sensitive data transmission over Ethernet networks. The goal is to develop protocols for high-availability and low-latency data transmission. Applications for this network protocol are real-time audio and video and real-time data for feedback control over data networks. TSN is an extension of the IEEE 802.1Q networking standard that supports virtual local area networks over an IEEE 802.3 Ethernet network, which makes it suitable for deployment over commercial wired and wireless networks with the additional security of virtual networking [3].

Table 4. TSN protocol standards under development.

Standard	Function group	Title
IEEE 802.1AS-Rev	Timing and Synchronization	Timing and Synchronization for Time-Sensitive Applications
IEEE 802.1Qbv	Forwarding and Queuing	Enhancements for Scheduled Traffic
IEEE 802.1Qbu	Forwarding and Queuing	Frame Preemption
IEEE 802.1Qca	Stream Reservation Protocol (SRP)	Path Control and Reservation
IEEE 802.1CB	Stream Reservation Protocol (SRP)	Seamless Redundancy
IEEE 802.1Qcc	Stream Reservation Protocol (SRP)	Enhancements and Performance Improvements
IEEE 802.1Qci	Forwarding and Queuing	Per-Stream Filtering and Policing
IEEE 802.1Qch	Forwarding and Queuing	Cyclic Queuing and Forwarding
IEEE 802.1CM	Vertical	Time-Sensitive Networking for Fronthaul
IEEE 802.1Qcr	Forwarding and Queuing	Asynchronous Traffic Shaping

Figure 15 shows the data frame structure of an Ethernet packet before it gets wrapped in the TCP/IP headers.

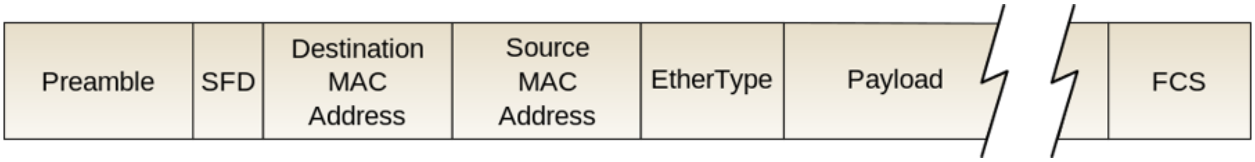


Figure 15. Ethernet frame structure. Start frame delimiter (SFD) = ; media access control (MAC) = ; frame check sequence (FCS) = .

An 802.1Q frame is indicated by setting the EtherType to the hexadecimal value 0x8100. TSN requires using switches/router that recognize and decipher EtherType, and not all do.

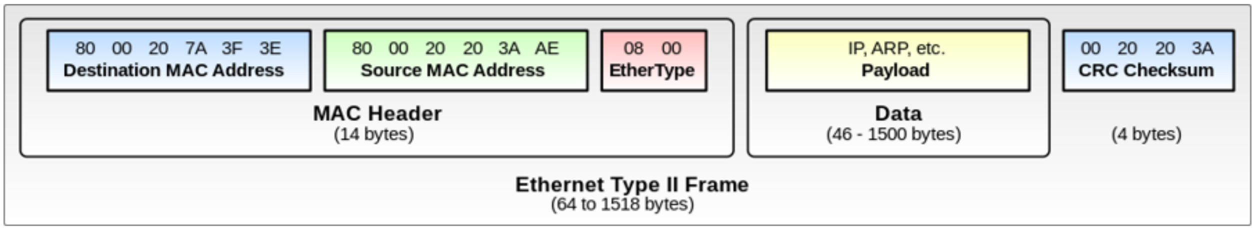


Figure 16. Example of an Ethernet type II frame. MAC = ; cyclical redundancy check (CRC) = .

3.3 CYBER PHYSICAL SYSTEMS

From a power grid control system perspective, the power grid is an example of a cyber-physical system in which the cyber system is defined as software, data transmission, and computation hardware and the physical system as the non-computational hardware that can be affected either directly or indirectly by the cyber system. This structure is common to networked control systems that are networked using a local area network or a wide area network.

In the simplest form of a networked control system, physical sensors measure a quantity of interest (e.g., voltage) locally, which is then converted to a digital number expressing the quantity of interest. This digital value is then sent over a data network to the controller, which contains decision-making algorithms that use the sensor values to determine actuation commands that are then sent over the network to the actuators that affect the physical system. The sensors then measure the system again and feed that information back to the controller over the network. This loop is repeated many times per second. This feedback loop requires some level of determinism to operate correctly. Figure 17 show some sources of non-determinism in the feedback loop.

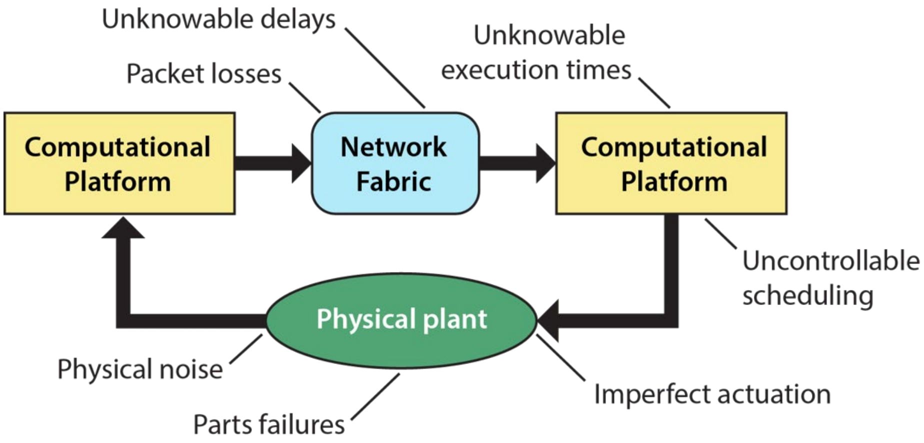


Figure 17. A feedback control loop description of a cyber-physical system.

The feedback architecture allows the system to be resilient to physical noise, failures, imperfect actuation, and uncontrolled scheduling. However, large variations in network transmission delays and software execution times along with packet losses can interfere with the operation of the control system. Low-speed processes have feedback cycle times in the 100s of milliseconds. Today, high-speed processes run the control loop at 250 ms. Figure 18 shows some typical control loop speeds for different applications. PROFINET (Process Field Net) and Sercos are two standard industrial controls communications protocols.

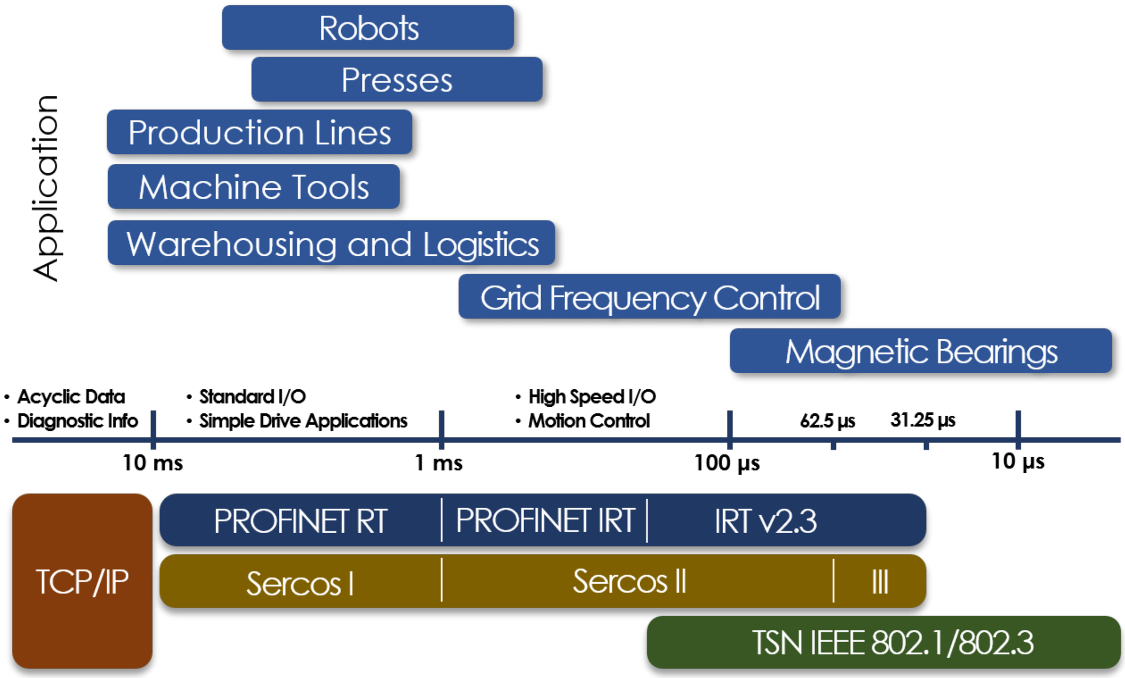


Figure 18. Typical control loop speeds. I/O = input/output. IRT = Isochronous real-time.

3.4 TSN AT EPB

To test the application of TSN to power grid control and situational awareness, ORNL partnered with EPB to deploy TSN using EPB's existing data network. EPB has one of the most advanced grid automation and control systems in the United States and its communications network is built on a fiberoptic ring network that handles all the SCADA information for EPB's service area. EPB also provides internet and video services to its customers through this fiberoptic network. Two substations, Riverside and Ridgedale, along with the EPB SCADA/IT control center, were chosen as locations to deploy and test the TSN hardware and software. Figure 19 shows the geographic locations of the deployment sites. Figure 20 show the placement of a fiberoptic loop back at the substation network terminal for testing the round-trip latency of the data stream. Figure 21 shows the integration of TSN with the existing network components. The primary test of the TSN performance is the effect that the increased bandwidth would have on the critical SCADA data currently being sent over the network. The secondary test is the achievable latency upper bound and bandwidth of the TSN virtual local area networks.

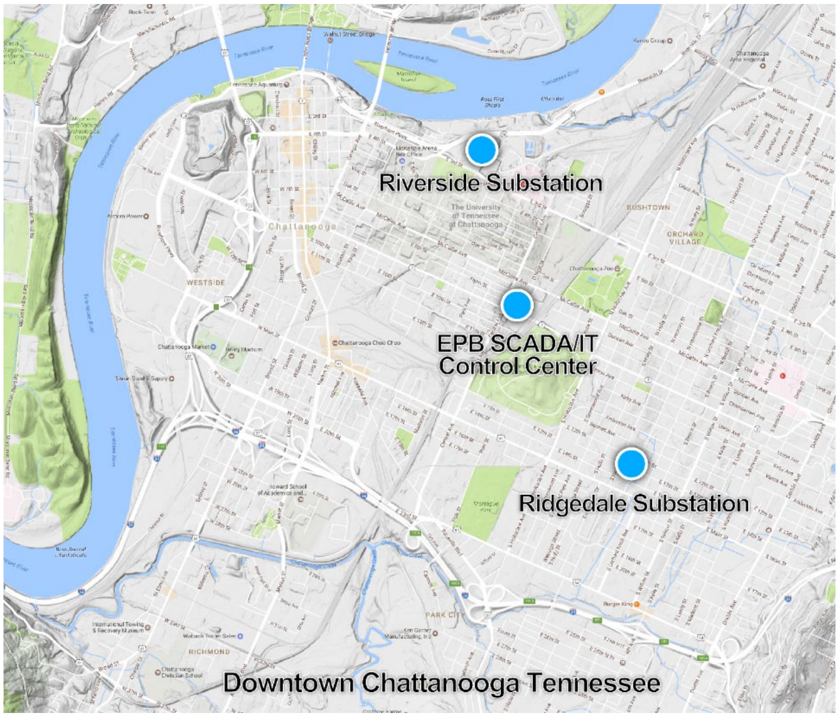


Figure 19. TSN testing locations.

Figure 20. Loopbacks placed in single-mode fiber trays.

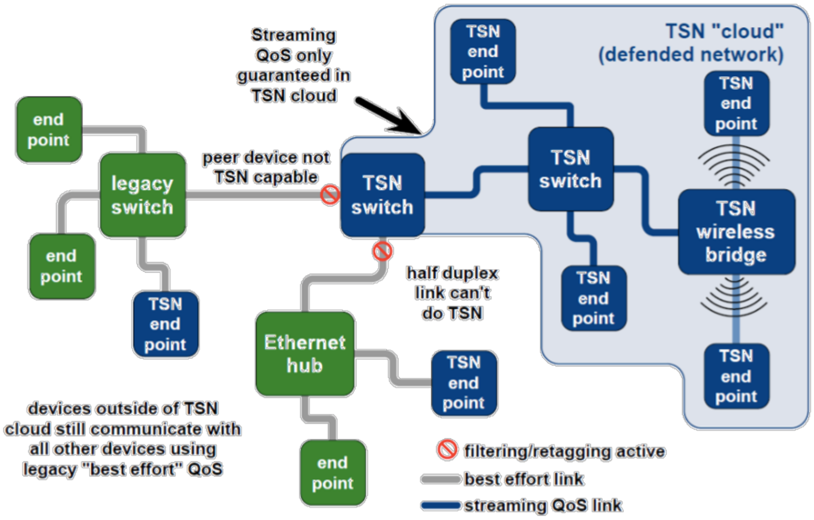


Figure 21. TSN interface with existing operational network components.

3.5 RESULTS

By injecting simulated data traffic into the TSN endpoints, the effect on the SCADA data was monitored by EPB at EPB's control center. Figure 22 shows that EPB measured no effect on its SCADA system data by the TSN data traffic.

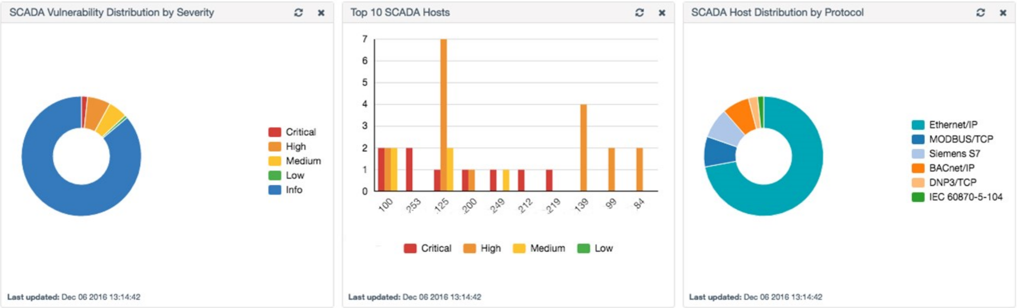


Figure 22. SCADA monitoring showing no TSN effect on current operations.

To test transmission speed and latency, a low-cost substation sensor suite was developed that included extended grid state and substation sensors identified by EPB as useful for operation and security. The units communicated wirelessly with a TSN bridge using 900 MHz communications. The units measured

- Temperature
- Humidity
- Motion (accelerometers and gyrosopes)
- Magnetometers
- Thermal imagery
- Visual cameras
- Cellphone signals
- Coronal arc discharge
- H_2
- Acoustics/sounds
- Solar irradiance

- Drone radio frequency detection

In addition to the extended grid state sensors, TSN could also relay commands to a drone with a full high-definition video camera. This allowed operators to remotely operate the drone from the command center and receive full high-definition video in near real-time for remote substation inspections.

Figure 23. Low-cost extended grid state substation monitoring, wireless TSN endpoint, and remotely operated inspection drone.

The high speed and low latency provided by TSN allowed the control center operator to easily operate the inspection drone.

4. DISTRIBUTED CONTROLS TESTING ON CSEISMIC

As more distributed energy resources (DERs) are integrated into the power grid, they will allow the grid to be more resilient to natural events such as storms or attacks on infrastructure. The tradeoff is a more complex system that needs better situational awareness and distributed control to maintain voltages and frequency within their nominal ranges, dynamically reconfigure the network topology to minimize the effect of faults, and extend the energy marketplace to commercial and residential consumers.

Network-connected microgrids are currently one solution for incorporating more DERs into the power grid. These microgrids allow a hierarchical division of the network topology to isolate the microgrid operation by disconnecting it from the distribution system and operate independently during storms or other events that disrupt the distribution system operation. Then, the microgrid can supply local power needs until the disruption has been resolved at which point the microgrid reconnects to the distribution system.

Software, hardware, and control are currently active areas of research in the power system and control communities as seen in refs. [4, 5, 6, 7] and the numerous references therein. Hardware-in-the-loop (HIL) testing of the control algorithms is challenging and not many test beds are available in the United States. However, distribution companies are hesitant to implement unproven technologies in their system without the confidence that comes from HIL tests.

In response to these challenges, ORNL developed the CSEISMIC application-based communications and controls software and HIL test bed for testing new control algorithms. As a part of the Grid Modernization Laboratory Consortium Southeast Regional Consortium project, CSEISMIC was applied to a HIL model of the EPB distribution control center microgrid. EPB is building this microgrid so that its main control center is self-sufficient during major storm events so it can continue to coordinate restoration and repair efforts in the event of a power loss.

The main goals of this task were to demonstrate performance and functionality on a real-world system and increase utility owners' confidence that when implemented in the field, the system would perform as expected.

To accomplish this goal, using detailed information about the EPB microgrid inverters, flow battery, solar cells, and topology, ORNL developed a dynamic model of EPB's microgrid components and implemented it on the ORNL Real-Time Digital Simulator (RTDS). The nonlinear dynamic models of the individual components were then integrated with the ORNL physical microgrid test bed that is a software-reconfigurable HIL test bed (SI-GRID) to emulate the network topology and communication network. This HIL implementation provided a safe environment to test the performance and functionality of the integrated system without the safety and reliability concerns of deploying the system on an operational microgrid and potentially affecting EPB's ability to monitor and control its distribution system.

After building the component models, selecting the inter-device communication protocols and control schemes used in EPB's distribution system control center microgrid, and setting up the physical interconnections of the components through the SI-GRID software-reconfigurable test bed, EPB engineers verified that the HIL test bed matched EPB's system. This provided confidence for EPB that the performance and functionality test results would be valid when the CSEISMIC controller is implemented on its distribution center microgrid.

4.1 CSEISMIC

CSEISMIC is an application-based communications and control framework used for deploying and testing new control and optimization algorithms and architectures. It is designed to be highly interoperable with both new and legacy DERs and communication protocols. It employs a publish/subscribe communication architecture that simplifies the integration of devices into the microgrid and reduces the required communications overhead. CSEISMIC includes a suite of standard libraries for legacy peer-to-peer communications protocols such as IEC 61850 and newer DER protocols such as OpenADR. It also has application-based optimization along with solar- and load-forecasting libraries. It uses seamless islanding and resynchronization algorithms developed at ORNL. The basic CSEISMIC functions are

- Grid-connected and islanded operation
- Islanding transition
- Resynchronization and reconnection

- Energy management
- Ancillary services

4.2 EPB MICROGRID

EPB has created an advanced control center that monitors more than 1,200 IntelliRupters for automated and manual reconfiguration of its power distribution network, 214 motor operated switches, and advanced meters at all 174,000 premises in its service area. EPB's network uses a fiberoptic communications system for all EPB's SCADA data and can automatically reconfigure itself to minimize the number of power outages during severe weather events. EPB is currently installing a vanadium flow battery, photovoltaic system, and power electronics to create a microgrid for its control center that can operate the control center during severe weather so that EPB can continue to monitor its distribution system and dispatch workers to repair damage that has occurred to minimize the time that premises are without power. This prevents significant economic losses for its customers because of severe weather events [8, 9]. In using CSEISMIC to control EPB's microgrid, the main functions are seamless islanding, resynchronization and reconnection, and frequency and voltage regulation when islanded. Another goal of the tests was to economically evaluate the effect of a flow battery as part of the EPB control center microgrid.

4.3 TESTING

To test the functionality of the CSEISMIC controller to operate the EPB control center microgrid, ORNL worked with EPB to develop an accurate model of EPB's microgrid that was then implemented on an RTDS real-time simulator as shown in Figure 24. The microgrid master controller integrates an energy management system with a SCADA system. The integrated energy device controllers are implemented on National Instrument CompactRIOs.

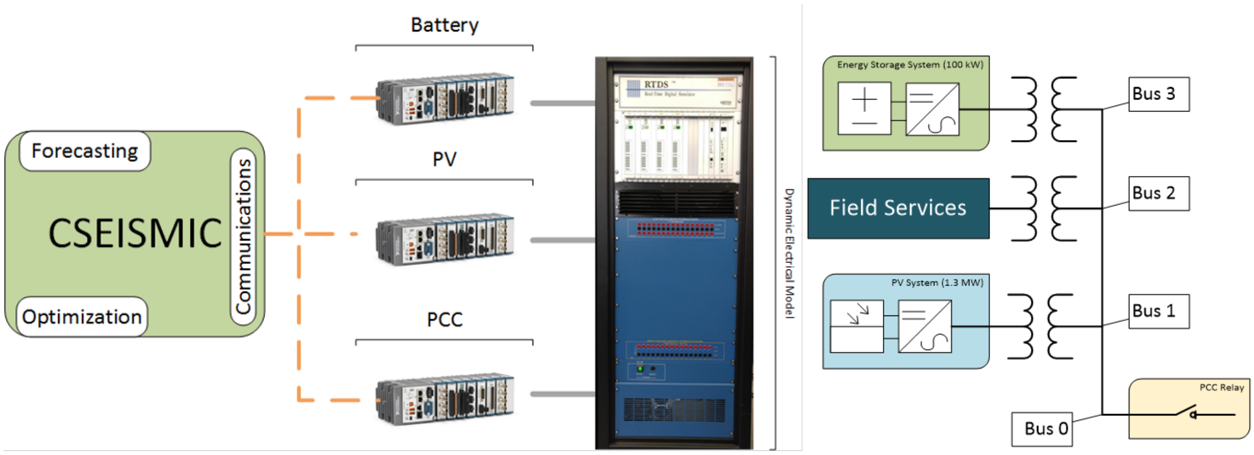


Figure 24. Architecture of the CSEISMIC test setup for the EPB control center microgrid tests.

Figure 25 provides a detailed architecture of the EPB control center microgrid. When the microgrid is in islanded mode, the photovoltaic (PV) system is disconnected because of its high output relative to the field services' power consumption.

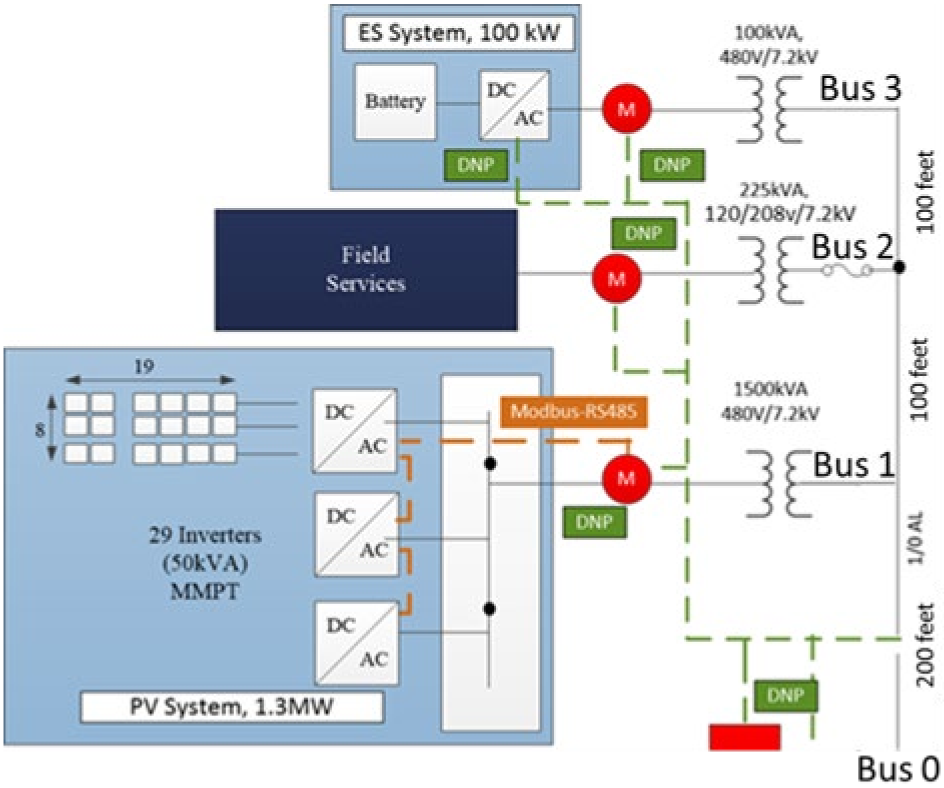


Figure 25. EPB microgrid architecture.

The vanadium flow battery energy storage controller runs on a National Instruments CompactRIO field-programmable gate array computer, which interfaces with the RTDS through analog input/output to control the energy storage system and inverter. This mimics the actual end-to-end communications in the microgrid.

During blue-sky operation when the microgrid in connected to the power distribution system, the photovoltaics operate at full power until an islanding signal is received. The battery charge/discharge curve is based on optimization of ancillary services such as peak reduction reduce overall costs. When an islanding signal is received, the PV disconnects before islanding. Then, the energy storage is dispatched to minimize the current through the point of common coupling between the microgrid and distribution system. Finally, after a settling time, the point of common coupling is opened disconnecting the microgrid from the distribution system and the energy storage transitions to voltage and frequency control mode to stabilize the microgrid voltage and frequency. Figure 26 shows the voltage and current at the microgrid point of common coupling when the microgrid is placed into island mode and resynchronized and reconnected with the distribution network.

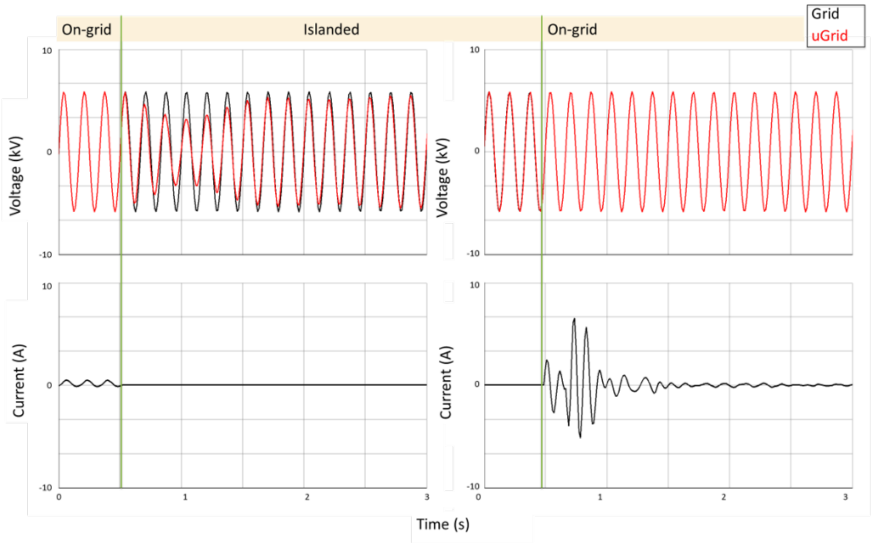


Figure 26. Islanding and resynchronization of the microgrid at the point of common coupling.

Figure 27 shows the energy storage matching the load before the microgrid switches to island mode, the transition of the energy storage to voltage/frequency control and the resynchronization to distribution system.

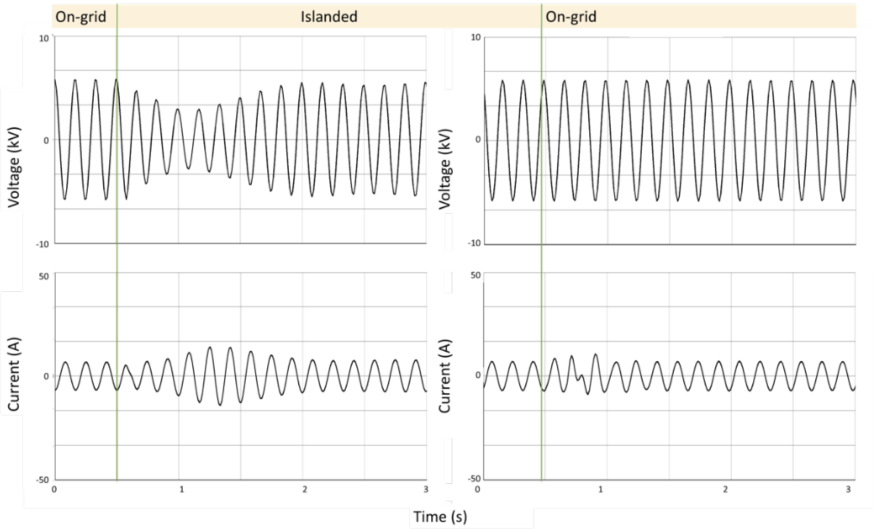


Figure 27. Energy storage system control signals and reponse during islanding and resynchronization.

Figure 28 shows the uncontrolled field services loads during the transition to island mode and their stabilization through the energy storage voltage/frequency control and subsequent seamless resynchronization with the distribution system.

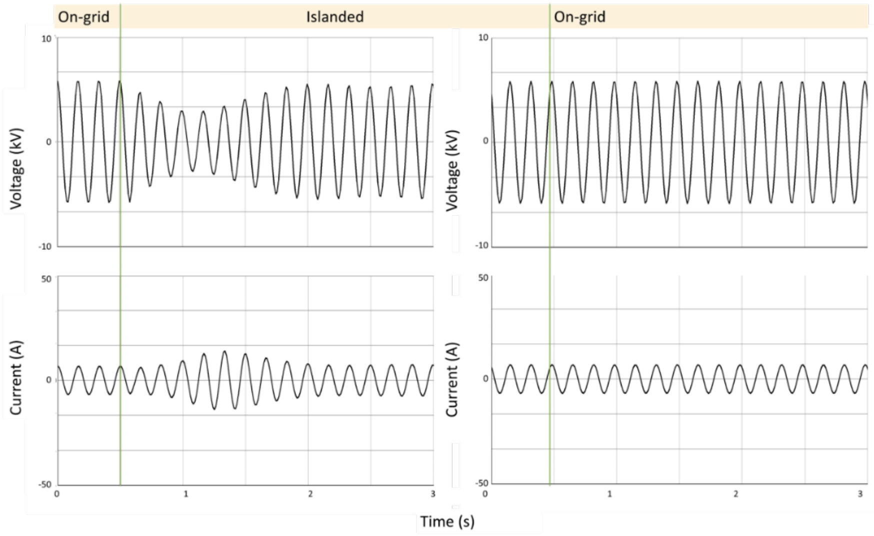


Figure 28. Field services load during islanding and resynchronization.

5. CONCLUSIONS

The increasing deployment of DERs will improve the resilience of the US power grid and expand market opportunities to residential and commercial premises. However, this comes at the cost of increased complexity, which requires the application of existing technologies to the power grid and the development of new technologies in deterministic communications, sensing, and control architectures and algorithms. In the course of this research and development project, ORNL and SRNL brought together regional stakeholders in the Southeast United States, including industry and universities, to develop a better understanding of the next technical challenges facing industry and the next technical solutions being developed by national laboratories and universities.

ORNL demonstrated new optical sensor technologies that will enable the application of step distance protection relays to power distribution systems. Step distance protection relays allow improved location of faults, more flexible network topologies, and bidirectional power flow. Currently, step distance protection is only applied on power transmission systems because their large phase angles can be measured by commercial sensors. ORNL demonstrated that the optical voltage and current sensors have the resolution needed to measure the small distribution system phase angles. Furthermore, ORNL developed a HIL test setup that demonstrated successful operation of the step distance protection using industry-standard impedance relay tests.

In collaboration with EPB, TSN technology was deployed on EPB's existing fiberoptic data network. Using EPB's SCADA monitoring system, it was shown that large sensor data sets being sent using TSN did not affect EPB's SCADA network traffic. TSN was also shown to have high enough bandwidth with low enough latency to remotely pilot a drone with full high-definition streaming video.

Finally, using the CSEISMIC communications and control architecture and the ORNL HIL test bed, the authors demonstrated that the EPB control center microgrid could be controlled and optimized to provide ancillary services when connected to EPB's distribution network. Seamless islanding, resynchronization, and reconnection were also demonstrated using the HIL test bed. This demonstration provided confidence that the controller implementation on the physical microgrid at EPB will be successful.

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