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Evaluation of SmartValve™ Devices Installation at Central Hudson



Evaluation of SmartValve™ Devices Installation at Central Hudson

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ABSTRACT

EPRI collaborated with Central Hudson Gas and Electric Corporation (Central Hudson) to observe a pilot installation of SmartValve™ and SmartBypass™ units with the objective of evaluating the functioning of the technology, identifying areas for improvement and areas for further analysis and investigation, and summarizing the findings and EPRI's experience into a technical document.

The pilot installation consisted of a small deployment of three SmartValve devices and the corresponding SmartBypass units at a 115 kV line that runs from the Sturgeon Pool substation to the Ohioville substation. The intention of this small deployment was for Central Hudson to gain experience with various aspects of the technology. EPRI's observation and evaluation work focused on the following key areas: installation process, communication and controls, cybersecurity, impact on protections, and impact on power system operations and reliability. The work performed by EPRI included two site visits.

This report describes the work performed by EPRI, including details on the information received and communication between EPRI and the Smart Wires team, and a summary of the findings and conclusions.

Keywords

Evaluation
Power flow
Control
Pilot installation
Cybersecurity
Communication

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PRIMARY AUDIENCE: Power system planning and operations staff, protection engineers, cyber security personnel, research and development staff

SECONDARY AUDIENCE: Transmission engineering and design staff; academia and R&D organizations pursing research on power system innovation and modernization

KEY RESEARCH QUESTION

Smart Wires Inc. has developed a new type of device to control power flow in transmission networks. The new technology is a Modular Static Synchronous Series Compensator (M-SSSC). A typical M-SSSC installation is comprised of two types of devices, the SmartValve™ that performs the power flow control over the transmission line, and SmartBypass™ that provides a unique method for rapid bypass during line faults.

The key questions addressed through this project are: What are the considerations for designing transmission solutions based on the use of M-SSSC devices? What can be learned about the technology readiness and performance from the pilot project at Central Hudson?

RESEARCH OVERVIEW

EPRI observed Central Hudson's installation of SmartValve and SmartBypass devices, evaluated the functioning of the technology based on the agreed project success criteria, identified and recommended areas for improvement or simplification, and summarized the findings and EPRI's experience into a technical report.

The pilot installation consisted of a small deployment of three SmartValve units and the corresponding SmartBypass units at a 115 kV line that runs from the Sturgeon Pool substation to the Ohioville substation. The intention of this small deployment was for Central Hudson to gain experience with various aspects of the technology. EPRI observation and evaluation work focused on the following key areas: installation process, communication and controls, cybersecurity, impact on protections, and impact on power system operations and reliability.

KEY FINDINGS

- The initial installation performed on February 2019 was smooth with no incidents
- For the control of SmartValve and SmartBtpass devices, Smart Wires uses wireless communication bands that are susceptible to interference, whether unintentional or intentional (jamming). Even though it may not be critical for secure operation of the devices, for larger installations EPRI recommended performing a comprehensive evaluation of the impact that loss of communications may have on system operation security.
- Regarding cyber security, EPRI observed that Smart Wires has put a lot of thought into their security architecture, hardware & software development, and resources into testing the product to limit the attack surfaces and vectors. However, additional work may need to be done by Smart Wires to satisfy all the host utility regulatory concerns.
- A desktop review of the equipment and performance found no significant impact on the performance of nearby protections , assuming that the SmartBypass units perform as advertised. Measurements were not available from digital fault recorders or protection relays in order to fully validate performance.

- During the demonstration test, EPRI observed that injection of series voltage through SmartValve units effectively changed power flow of the transmission line. The devices responded through the control command both locally through the SmartInterface, and remotely from SCADA/EMS.

WHY THIS MATTERS

SmartValve is a new generation of power flow control devices with some salient features such as modular and scalable configuration. They can be used in some cases to design cost-effective solutions for a variety of transmission system needs. SmartValve can be applied also in cases where series compensation is needed but the use of conventional series capacitors is not feasible because of sub-synchronous resonance problems.

The pilot project performed by Central Hudson provides very valuable insight into the capabilities, readiness level, and performance of these devices. The lessons learned through the pilot demonstration and EPRI evaluation documented in this report are expected to help other entities make risk-informed decisions about the use of this technology for different types of transmission system applications.

HOW TO APPLY RESULTS

Transmission planning staff can learn from the results of the pilot project documented in this report as a result of the EPRI independent evaluation. Planners can find details of SmartValve devices and relevant observations and considerations for the use and implementation of this technology in transmission systems. It is hoped that this enhanced understanding of the technology will raise further awareness about its capabilities and limitations, and help accelerate adoption in cases where it may result in preferred alternatives.

LEARNING AND ENGAGEMENT OPPORTUNITIES

The work performed under EPRI project P40.24 is closely related to this evaluation. The objectives of the P40.24 project include:

A. development of a comprehensive guide for planning and operations engineers to better understand the main technical, operational, and economic characteristics of traditional and emerging power flow control technologies, as well as to provide reference and guidance on potential uses and operation practices, and

B. development of methodologies and software tools to help planners evaluate and design cost-effective power flow control solutions, in combination with other advanced technologies (i.e.: energy storage) and traditional expansion projects such as new lines and substations.

The SmartValve is one of the technologies considered in the project, for both the power flow control reference guide and the software tool for transmission solution design.

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PROGRAM: P40 (Transmission Planning)

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CONTENTS

ABSTRACT ..... **V**

EXECUTIVE SUMMARY ..... **VII**

1 **INTRODUCTION** **1-1**

Background 1-1

Objective 1-2

Approach 1-2

Report Structure and Content 1-3

Documentation Received 1-3

2 **BACKGROUND** **2-1**

General Description of SmartValve™ and SmartBypass™ 2-1

SmartValve and SmartBypass Installed at the Ohioville Substation 2-4

3 **INSTALLATION PROCESS** **3-1**

Introduction and Objective 3-1

Installation Process 3-2

Summary of the Information received 3-5

Observations and Conclusions 3-6

Updates 3-6

4 **COMMUNICATION AND CONTROLS** **4-1**

Introduction and Objective 4-1

Summary of the Information Received 4-1

Evaluation During Installation 4-4

Field Tests and Commissioning Plan June 2019 4-5

Review and Evaluation During Field Demonstration 4-5

Observation and Conclusions 4-6

***5* CYBERSECURITY 5-1**
Introduction and Objective 5-1
Approach 5-1
Summary of the Information Received 5-1
Findings and Observation 5-2

***6* PROTECTION IMPACT 6-1**
Introduction and Objective 6-1
Bypass of the SmartValve and Grid Protection 6-1
Failure to Bypass on the Faulted Phase During a Fault 6-3
Failure to Bypass on the Unfaulted Phase(s) During a Fault 6-4
Different Control Modes or Operating Status Between Phases 6-4
Approach 6-4
Summary of the Information Received 6-5
Observation and Conclusions 6-5

***7* POWER SYSTEM IMPACT 7-1**
Introduction 7-1
Review and Evaluation During Field Demonstration 7-1
Injection Test Procedure 7-1
Injection Test Through Human Machine Interface (HMI) 7-1
Injection Test Through SCADA 7-2
Test Results 7-3
Observation about Potential Impact to the System 7-5

***8* CONCLUSIONS 8-1**
Observations from EPRI's Work 8-1
Pilot Learnings 8-3
Other Observations 8-3

***9* REFERENCES 9-1**

***A* RESPONSES TO EPRI QUESTIONS A-1**

LIST OF FIGURES

Figure 2-1 SmartValve – (a) system diagram and (b) operating range (Source: [1]) 2-2
Figure 2-2 0.5 MVAr SmartValve [1] 2-3
Figure 3-1 Installing the upper cross arms 3-2
Figure 3-2 Installing the SmartBypass units 3-3
Figure 3-3 Installing the SmartValve units 3-4
Figure 3-4 Final installation Image 3-5
Figure 3-5 Overall view of the installation with the implemented changes 3-6
Figure 4-1 Basic diagram of the communication system 4-1
Figure 4-2 Typical rack configuration 4-2
Figure 4-3 Basic electrical configuration of SmartValve and SmartBypass devices 4-3
Figure 4-4 Pole Installation with antennas on control room [Source: Smart Wires] 4-4
Figure 5-1 Security features of communication and control of SmartValve installation 5-2
Figure 6-1 SmartValve model 0.5-900 injection characteristic 6-2
Figure 6-2 SmartValve and SmartBypass system diagram 6-2
Figure 7-1 Replica of SCADA screen projected onto the wall of the substation control room – Monitoring mode 7-2
Figure 7-2 Replica of SCADA screen projected onto the wall of the substation control room – Capacitive injection mode (500 V) 7-3
Figure 7-3 Line current variation during injection test 7-5

LIST OF TABLES

Table 3-1 Construction standards 3-5
Table 7-1 Injection test results 7-4

1
INTRODUCTION

Background

Central Hudson Gas and Electric Corporation (Central Hudson) is a regulated gas and electric utility serving the Hudson Valley of New York State. The Company provides electric and gas transmission and distribution (T&D) services to approximately 302,000 electric customers and 80,000 natural gas customers. The Central Hudson service territory extends from the suburbs of metropolitan New York City north to the Capital District in Albany covering approximately 2,600 square miles. Headquartered in Poughkeepsie, New York, Central Hudson is a subsidiary of Fortis Inc. and is a participating member in the NYISO (New York Independent System Operator) electricity market.

As part of the NYISO, Central Hudson takes part in annual planning processes including reliability needs, economic projects, public policy projects and interconnection procedures. NYISO's standard interconnection procedures for large facilities (all generators larger than 20 MW and merchant transmission) are described in the Open Access Transmission Tariff (OATT) Attachments S & X. In the final study of the NYSIO Interconnection Process, the impact of all Class Year generators is assessed, as a whole, on the system. This is called the Class Year Facilities Study. For capacity resources, this includes a System Deliverability Study. If a Transmission Interface is found to constrain Capacity Deliverability, a System Delivery Upgrade (SDU) is proposed.

As part of the Class Year 2009, 2010, and 2011 the System Deliverability Studies found that the UPNY-SENY interface was constrained. NYISO proposed 21% series compensation on the 345 kV Leeds-Hurley Ave line to enable full capacity deliverability of all Class Year projects. Local relay replacements and potential sub-synchronous resonance (SSR) mitigation were also part of the proposal.

Central Hudson and National Grid collected security from the developers impacting the UPNY-SENY interface and this security collection has reached a value where construction of the SDU has been triggered. Central Hudson and National Grid are now obligated to initiate construction of the SDU project.

Based on Central Hudson's experience with the Marcy South Series Compensation and a preliminary UPNY-SENY protection study, traditional series compensation systems were likely to cause significant impacts on area protection schemes. Central Hudson anticipated relay upgrades due to voltage reversal, the possibility of current reversal and sub-harmonic frequency transients. These modifications would add significant costs to the project.

Central Hudson evaluated the use of an alternative power flow control technology based on the Static Synchronous Series Compensator (SSSC) combined with a unique method for rapid bypass during line faults. The modular SSSC (M-SSSC), is a member of the M-FACTS (modular

Flexible AC Transmission System) family of devices. Central Hudson's analysis concluded that this solution will have significantly less system impacts resulting in lower costs and provide additional benefits compared to the originally proposed series compensation.

In order to gain familiarity with the technology in-advance of the full solution's installation, Central Hudson decided to install a small deployment of M-SSSC technology for a trial period, in-advance of a larger deployment. This initial experience involves an installation of three SmartValve devices and three SmartBypass devices. Through this smaller scale deployment, or demonstration project, Central Hudson expected to gain experience with various aspects of the technology.

The pilot installation consisting of three SmartValve devices with their corresponding SmartBypass devices were installed on Central Hudson's 115 kV "OR Line" that runs from the Sturgeon Pool Substation to the Ohioville Substation.

Objective

The objectives of this project were for EPRI to observe Central Hudson's installation of SmartValve and SmartBypass devices, evaluate the functioning of the technology based on the agreed project success criteria, identify and recommend areas for improvement or simplification, and summarize findings and EPRI's experience into a technical report.

Approach

The evaluation performed by EPRI consisted of the following activities:

1. **Information gathering and analysis**

   Throughout the project EPRI requested relevant documentation about the SmartValve and SmartBypass devices, as well as specific details of the pilot installation at Ohioville Substation, including device manuals and application guides, technical reports from previous studies, test plans, test results and reports, technical papers, construction drawings and diagrams. EPRI also conducted several phone calls and in-person interviews with Smart Wires and Central Hudson personnel to collect further details.

2. **Review and evaluation during installation**

   The EPRI team was present during the installation of the three SmartValve and SmartBypass devices at the Ohioville Substation, which took place in February 2019. The objective was to observe the installation process to document the main observations and look for efficiencies that may speed up and facilitate the installation when Central Hudson begins the larger deployment on the 345 kV Leeds-Hurley Ave line. This included the installation of the devices and the associated communications equipment.

3. **Review and evaluation during field demonstration**

   A field demonstration was conducted on June 25, 2019. The objective was to show how the commissioning process is performed and verify the functionality of the devices through operational test.

The field demonstration included:

- Re-initialization of the communication network: This test was done to observe if the communications equipment powers up and connection between all components is verified (all components join the network, reauthenticate, and communicate).
- Injection test via Human Machine Interface (HMI): This test was to verify that the devices were able to be controlled locally from the substation through the SmartInterface™. It included verification of signals sent from the HMI, the devices' response, and HMI verification of response.
- Injection test via SCADA: This test was to verify that the devices were able to be controlled remotely from the SCADA/EMS.

The injection tests were also used to verify the impact of the devices' control on the power system operation. More specifically, the injection tests were used to evaluate if an increase in line current occurs when the devices enter in capacitive injection mode, and conversely, if the line current decreases when the devices operate in inductive injection mode.

It should be mentioned that this field demonstration was not the actual commissioning performed by Smart Wires, but rather a demonstration of the installation functioning and basic performance. The commissioning involved a comprehensive set of test and verification processes as described in the Field Tests and Commissioning Plan developed by Smart Wires.

EPRI observation and evaluation work focused on the following key areas:

1. Installation process
2. Communication and controls
3. Cybersecurity
4. Protection impact
5. Power System impact

Report Structure and Content

This report consists of the following sections: Section 2 provides a brief description of the Smart Wires devices used in this demonstration, and of the main characteristics of the pilot demonstration. Sections 3 to 7 document the approach, results, and specific conclusions for each of the topical areas, namely: physical installation, communications and controls, cybersecurity, protection impact, and power system impact respectively. Finally, Section 8 summarizes the main conclusions.

Documentation Received

The following are reference documents provided by Smart Wires:

- SmartValve™ Application Guide 2019
- Communication & Control Overview, February 2019 (presentation)

- TEST REPORT, Report Number: 103758643MPK-002, Project Number: G103758643 - January 29, 2019. Testing performed on the SmartBypass™ Model Number: SmartBypass 2000
- Calculation Package - Central Hudson Gas & Electric Corporation SmartValve and SmartBypass Pilot Project
- Central Hudson System Ohioville Substation RF Network Verification, May 24, 2019 (report)
- Power System Protection Study - RTDS Tests on Smart Wires Products, DNV GL Document No.: 10058667-R-01. Issue Date: 30 April 2018 (Report)
- Smart Wires, Project Update. May 23, 2019
- Smart Wires, Field Tests and Commissioning Plan. June 2019

Apart from this documentation, over the course of the project, there were numerous phone conversations and communications via email between EPRI and the Smart Wires team, where specific aspects were discussed, and additional information was provided. Central Hudson participated and moderated those communications.

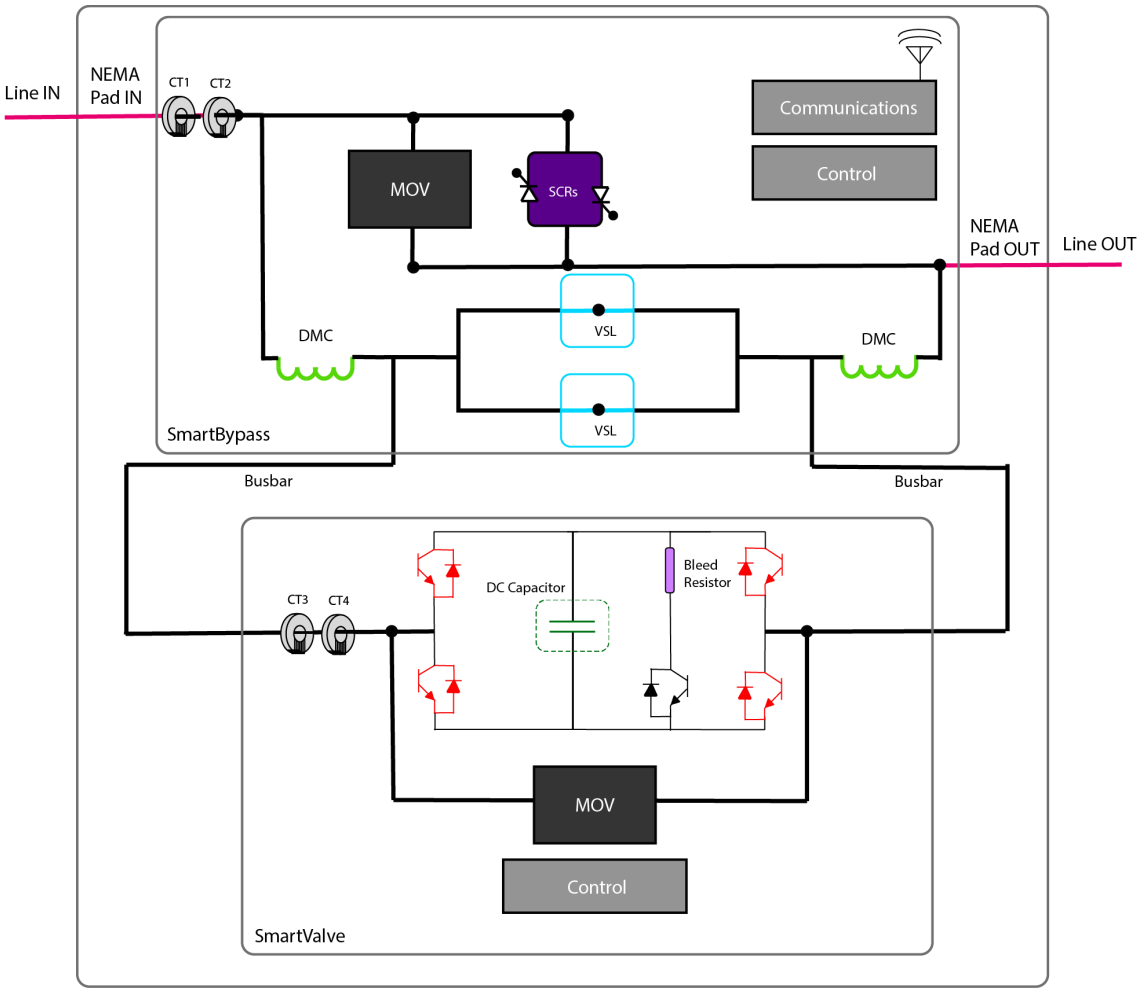
2
BACKGROUND

General Description of SmartValve™ and SmartBypass™

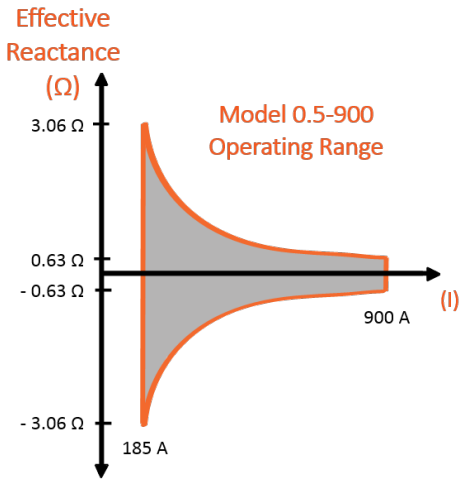
The SmartValve™ is a modular Static Synchronous Series Compensator (M-SSSC) developed by Smart Wires Inc. The main idea behind the M-SSSC concept is to provide a modular solution that can be quickly installed and uninstalled, allowing the solution to be scaled or moved as the needs of the grid change.

The SmartValve works by injecting a leading or lagging voltage in quadrature with the line current, effectively increasing or decreasing the reactance of a given circuit. Hence this device can "push" power away from or "pull" power on to various lines to divert current from overloaded lines to underutilized circuits. The SmartValve provides similar functionality of a series capacitor or series reactor but does not have the negative characteristics of these passive devices such as the risk of sub-synchronous resonance with series capacitors. The SmartValve operates at line potential and has no connection to ground.

Figure 2-1(a) illustrates the basic electrical configuration of the SmartValve. The device acts as a solid-state synchronous voltage source, consisting of a voltage-sourced inverter as shown by the single-phase H-Bridge. The H-Bridge control circuitry measures the line current through CT3 (current sensor) and determines the magnitude of the voltage injected into the transmission line to maintain a desired reactance. Figure 2-1(b) shows the response of a 0.5 MVAr -rated SmartValve with a maximum continuous current rating of 900 A RMS and with a maximum output voltage of ±566 V RMS of the fundamental transmission line voltage. The figure plots the effective reactance injection as a function of line current. The orange boundary of the operating range represents the maximum reactance available as a function of line current, which is achieved when the voltage output injection is kept at a constant ±566 V RMS. The grey area inside reflects the feasible range of operation if the output voltage is varied lower than ±566 V RMS of the fundamental [1]. The MVAr capabilities, maximum continuous current rating, and voltage injection values discussed in this report correspond with the devices installed at Central Hudson's Ohioville Substation. The SmartValve product line offers a variety of MVAr ratings (1 – 10 MVAr), maximum continuous current ratings (900 – 3,600 A RMS), and voltage injection (±566 – ±5660 V RMS).



(a)



(b)

Figure 2-1
SmartValve – (a) system diagram and (b) operating range (Source: [1])

Figure 2-2 shows a single-phase, SmartValve with a 0.5 MVAr rating. Typically, SmartValve units are installed across all three phases.

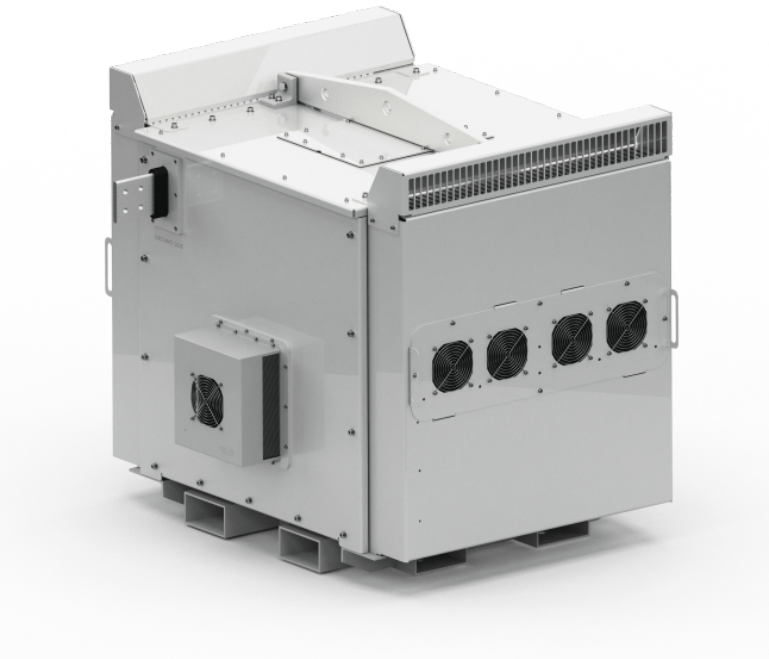


Figure 2-2
0.5 MVAr SmartValve [1]

The SmartValve works in conjunction with a fast-acting bypass (SmartBypass) for protection and control (Figure 2-1(a)). Under normal operation the bypass allows operators to switch the SmartValve in series with the utility's network facility. The SmartBypass also provides fast protective action during line fault conditions. When the SmartBypass senses a line current indicative of a line fault, it automatically fires the fast-acting antiparallel SCR switches, bypassing the SmartValve within 1 millisecond. The bypass can operate at line currents of thousands of amps during normal operation and can withstand fault currents of up to 63 kA RMS for a duration of up to 1 second. The bypass can also be closed in steady-state conditions. In that case the operating mode is called "monitoring mode" since, even though voltage injection is not enabled, telemetry information is still sent back via the communication system to the substation.

A SmartValve deployment can operate in four possible control methods:

- Injection at a fixed voltage: The SmartValve fleet is set to output a fixed voltage injection that is either capacitive or inductive. In this control method, the injected reactance will vary as the line current changes.
- Injection at a fixed reactance: In this control method the SmartValve fleet is set to emulate a fixed reactance that is either capacitive or inductive. In this control method, the injected voltage will vary as the line current changes to keep the reactance at a set value.
- Current control: In this control method the SmartValve fleet actively regulates the magnitude of the current through the facility to stay below a given level or equal a given level.

- Set-point control: In this control method the SmartValve fleet is set to output a preset reactance or voltage. The operator may choose among various presets.

SmartValve and SmartBypass Installed at the Ohioville Substation

The SmartValve installed at the Ohioville Substation is the model SmartValve 0.5-900. The ratings are follows [1]:

- Maximum continuous current (A RMS): 900 A
- Max Voltage Injection at 50 Hz and 60 Hz (V RMS): ± 566 V
- Max 2-Hour Emergency Current (A RMS): 990 A

3
INSTALLATION PROCESS

Introduction and Objective

The objective of this task was to observe the installation of the SmartValve and SmartBypass devices to document the main observations and look for efficiencies that may speed up and facilitate the installation when Central Hudson begins the larger deployment on the 345 kV Leeds-Hurley Ave line.

SmartBypass and SmartValve units were installed on transmission dead end structures (structures 117355,117356 &117357) located directly outside of the Ohioville Substation. Certain modifications had to be made to allow successful installation of the three SmartBypass units and the three SmartValve units. Three 55 foot poles, direct embed, dead end structures were utilized. Because the Smart Wires units are installed at line potential, additional considerations had to be made for the installation. Four separate cross arms needed to be installed at the steel poles and post and suspension insulators were installed to support the weight of the units and maintain proper clearance. Insulated guys had to be installed on the steel structures to ensure proper clearance to ground.

The SmartBypass and SmartValve units weight approximately 1526 lbs. each. They measure approximately 52 inches in length, by 49 inches in length by 52 inches in height.

The SmartValve and SmartBypass units enter monitoring mode when the line load current exceeds approximately 90 A. The system can begin injecting voltage at 185 A line load. The devices installed at Ohioville can inject ±566 V RMS into the line during operation, thus enabling it to increase reactance by up to 3.06 ohm on each phase.

The Smart Wires devices communicate via radio frequency (RF) with the control equipment located in the Ohioville Substation control house. Four RF antennas were installed at the substation control house, two 900 MHz antennas and two 2.4 GHz antennas. Multiple antennas were used in this pilot project to provide redundancy and to allow for tests of the redundant communications network.

A new relay panel was installed in the substation control house for the Smart Wires communication equipment. An SEL-3355 computer, two PowerLine Coordinators™ (Smart Wires Devices), two PowerLine Gateways™ (Smart Wires Devices) and two SEL-2730M Managed Ethernet Switches were installed in the relay panel. Communications between SCADA and the SmartBypass and SmartValve is performed by the PowerLine Gateway and PowerLine Coordinator. The PowerLine Coordinator utilizes RF communications to the SmartBypass and SmartValve. The PowerLine Gateway collects telemetry data from the units and provides communication between the SmartInterface™ and the RTU for supervisory control and data acquisition. SmartInterface software was installed on the SEL-3355 computer in the substation.

Installation Process

The first phase of the installation began by installing the aluminum cross arms on the three-steel structures outside the Ohioville Substation. Once the aluminum cross arms were in place, suspension insulators were installed on the cross arms for the installation of the SmartBypass units. The suspension insulators position the bypass in such a way as to create sufficient spacing. Since the SmartBypass is operated ungrounded, but energized, special precautions had to be taken into consideration when planning the positioning. The number of bells on the transmission line insulator string was not necessarily used for voltage considerations but was used to help position the bypass into the designed location specified by the engineering drawings.

During one point in the installation, it was noticed that one of the cross arms was installed upside down. Being installed upside down caused one of the suspension insulator strings to hang down too close or closer than desired to one of the steel poles. At that point the aluminum cross arm was taken down and turned over to its correct positioning. This positioning allowed for the suspension insulator string to hang down closer to the center of the two steel poles.

Post insulators were then mounted to each of the steel poles to help ensure the movement of the SmartBypass unit was kept to a minimum. The post insulators were installed on the steel poles and the other end was connected to a mounting bracket on the bottom of the SmartBypass. The bracket mount on the bottom of the bypass was designed in such a way as to be adjustable and made for an easy placement and installation of the bracket.



Figure 3-1
Installing the upper cross arms

Once the SmartBypass units were installed, the installation moved to phase two. During phase two, two additional aluminum cross arms were installed on the steel poles. This time they were installed below the SmartBypass units. Six post insulators were mounted on the aluminum cross arms, three on each side. These posts would later be utilized for the cables to connect the SmartBypass units and the SmartValve units. Suspension insulators were later connected to the aluminum cross arms to enable the installation of the SmartValve units.

The SmartValve units were installed on the suspension insulators. Again, the suspension insulators were used to place the SmartValve units in the correct position for installation not necessarily for the spacing needed for the 115kV voltage separation. The SmartValve units are also operated ungrounded at line voltage.



Figure 3-2
Installing the SmartBypass units

Post insulators were installed on the steel poles to help keep the movement of the SmartValve units to a minimum. The post insulators connected to a mounting bracket that attached to the underneath of the SmartValve. The SmartValve also had the adjustable connection point for the mounting bracket which helped make the connection of the bracket much easier.

The third phase of the installation was to connect the cables and the control cables for connecting the SmartBypass units to the SmartValve units. 750 MCM copper was chosen for the installation for its current carrying capabilities. The source side of the line was connected to the NEMA pad on the SmartBypass units. The output of the SmartBypass units was connected to the input for the SmartValve units. The outputs of the SmartValve units were connected to the input of the SmartBypass units and the SmartBypass units were connected to the line side of the line. Control

cables were attached from the SmartValve units to the SmartBypass units to allow communication between the units.



Figure 3-3
Installing the SmartValve units

Once the cable connections were completed, avian issues were discussed. With the way the installation was designed, there was the potential for avian species to come in contact with voltage variations if they were to land or try to nest on certain areas of the SmartValve units. A solution was developed utilizing 25 kV tape. The linemen covered any exposed connections close to the units and other exposed voltage carrying parts with the 25 kV tape (heavy duty electrical tape). This solution provided a novel and appropriate solution to the majority of the avian issues that could be thought of from the installation team.



Figure 3-4
Final installation Image

Summary of the Information received

Central Hudson and EPRI received construction drawings for the installation as well as “red line” drawings of the as built installation. The drawings can be found in the calculation package provided by Smart Wires.

Central Hudson and EPRI were also provided with the Calculations Package that included the construction calculations for the installation. See Table 3-1 Construction standards for a brief list of some of the standards to which the installation was designed. Since these were existing structures some design parameters were assumed to be correct and were not addressed.

Table 3-1
Construction standards

Parameters	Guidance
Minimum Clearance for 115 kV - vertical clearance to roadway	NESC 2017 Table 232-1
Minimum Clearance for 115 kV - Horizontal clearance between wires, conductors or cables at supports to conductors of different circuits	NESC 2017 Table 235-1
Minimum Clearance for 115 kV - Clearance of line conductors	NESC 2017 Table 235-6
Swing Clearances	N/A
Loading Gust Response Factor for Pole and Equipment (GRF)	NESC 2017 Table 250-3
Velocity Pressure Exposure Coefficient for Pole and Equipment (kz)	NESC 2017 Table 250-2
Weather Data for Equipment Loading – Grade B Construction	NESC 2017 Table 250-1

The structure was modelled and analyzed in PLS-POLE software and it was determined that the existing poles were adequate to support the equipment loading without modification. Due to the potential of design changes during the installation this analysis included a 20% increase in loads to account for any unknowns.

Observations and Conclusions

The total installation time required approximately 24 hours for a five-person crew. No special trucks were necessary during the installation; the crews utilized their usual work trucks. The weather conditions during the installation included freezing temperatures, gusting winds, and snow.

Updates

On May 23, 2019, Smart Wires provided a project update describing changes and improvements made to the physical installation. The main changes implemented in the original installation include [7]:

- New galvanized steel crossbeams were added to connect the poles and support the devices
- Post insulators were added to the poles to provide lateral stability
- Suspension insulators were added to the crossbeams to support the device weight
- In-line insulators were added to existing down-guys to maintain proper electrical clearances
- The jumpers between the line and SmartBypass and between the SmartBypass and SmartValve made of 795 ACSR were replaced by 750 MCM Copper, which are more flexible for an easier installation.
- Insulating tape was added to protect against wildlife since there is a differential potential between the jumpers and the device enclosure. (PR-000436)



Figure 3-5
Overall view of the installation with the implemented changes

4
COMMUNICATION AND CONTROLS

Introduction and Objective

The purpose of this task was to evaluate the performance of the SmartValve communication system during installation and commissioning test process, as well as provide observations related to communication system design and characteristics.

Summary of the Information Received

The overview presentation provided by Smart Wires contained a basic diagram of the communications paths, which is copied below in Figure 4-1.

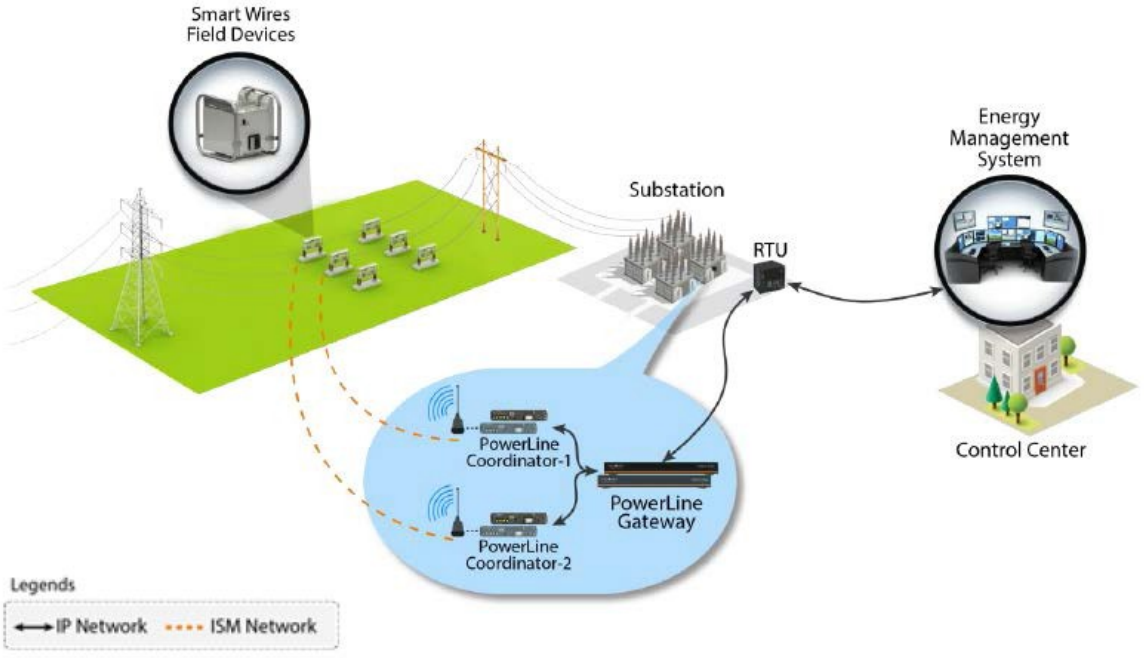


Figure 4-1
Basic diagram of the communication system

Variations of this diagram are repeated in the Communications and Control Overview presentation with additional detail for optional configurations and a recommended configuration for integration with the EMS. Also, included in the Communications and Control Overview presentation is a diagram of the backplanes of the PowerLine Coordinator and PowerLine Gateway devices in the control house and how they are cabled out to the antennas and to the utilities' SCADA and/or EMS (Figure 4-2).

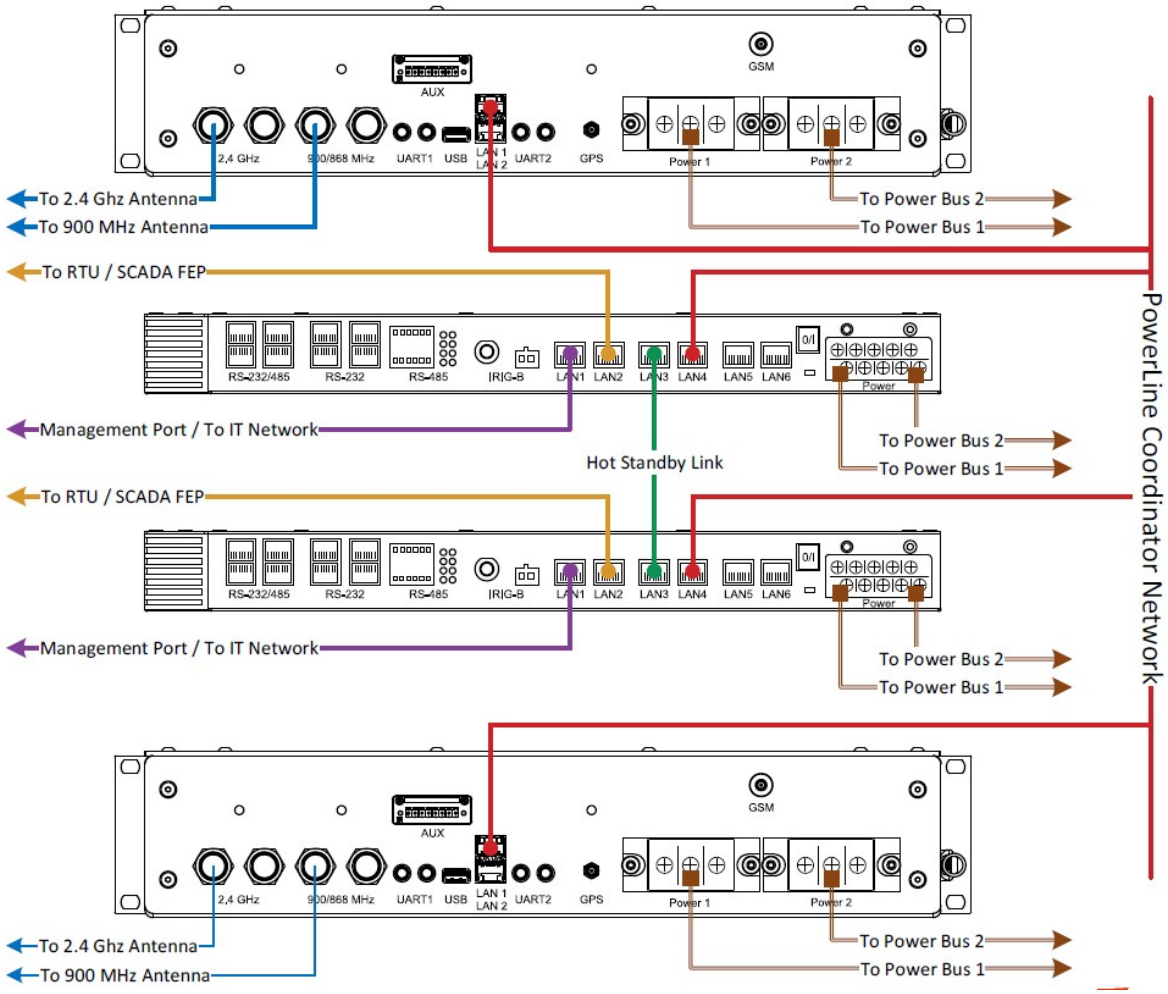


Figure 4-2
Typical rack configuration

During the Q&A portion of the Communications and Control presentation it was learned that the system uses two different unlicensed spectrum bands, these being 900 MHz and 2.4 GHz. Use of these bands for wireless communications in the U.S. are subject to regulations of the Federal Communications Commission (FCC) under 47CFR, Part 15. Prior to establishment of the FCC Part 15 rules these bands were in use for ISM (industrial, scientific, and medical) equipment, under Part 18 of the FCC rules. Part 15 use is secondary to Part 18 use.

Smart Wires uses 2.4 GHz for inter-phase communication between the SmartBypass units, and 900 MHz is used between the PowerLine Coordinator and the SmartBypass. The SmartBypass

communicates with the SmartValve via fiber optic connections bundled inside the power/control cabling.

It was further explained that the communications between the PowerLine Coordinator and the SmartBypass/SmartValve field units is not critical to the moment to moment functionality of the system but is necessary to change settings or query status. The SmartBypass and SmartValve each contain their own control boards but as mentioned above, only the SmartBypass has wireless communications, and therefore all messages between the PowerLine Coordinator and

SmartValve must pass through the SmartBypass. This is shown in the diagram shown in Figure 4-3, which is taken from the SmartValve application guide.

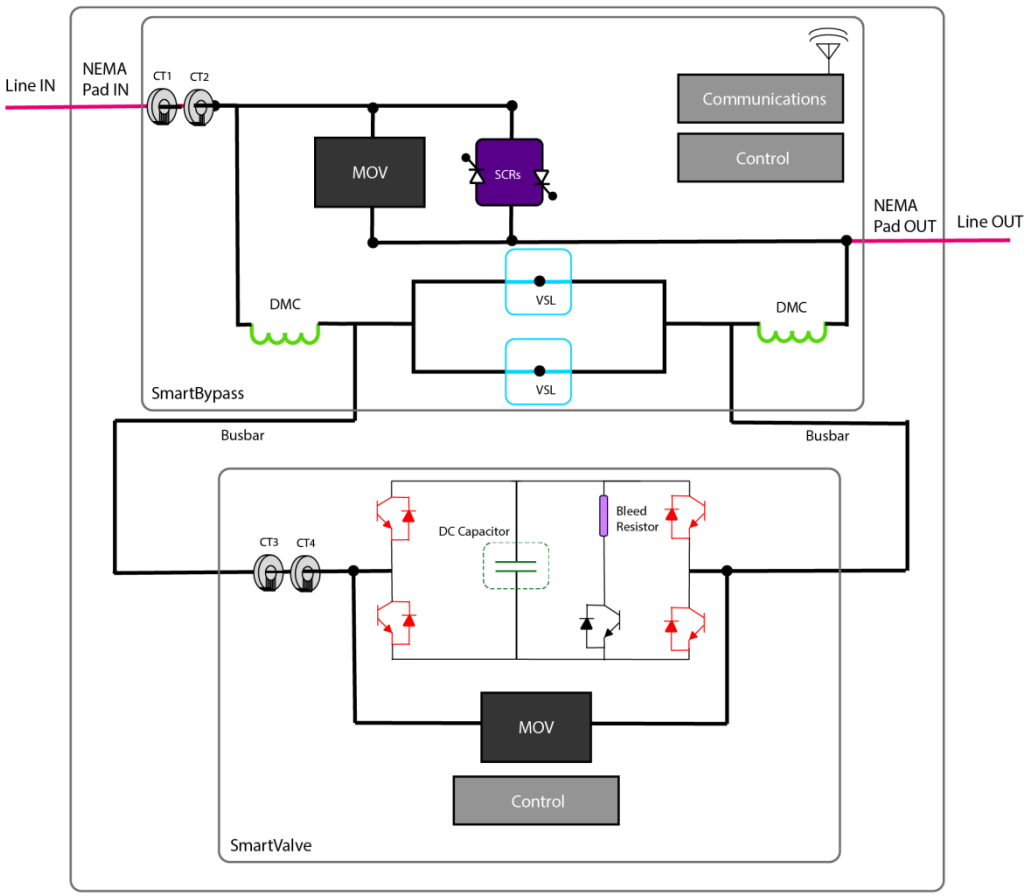


Figure 4-3
Basic electrical configuration of SmartValve and SmartBypass devices

Smart Wires provided certification laboratory test reports for the 900 MHz and 2.4 GHz radios in the SmartBypass. These reports contain the FCC IDs, QPS01005, and QPS01006 respectively.

The PowerLine Coordinator, which is the indoor equipment and as described above, only has a 900 MHz transmitter. The unit examined in the field had a label with the FCC ID QPS01004.

The FCC Part 15 application file for the PowerLine Coordinator was found at the FCC website. The file contains several documents, including the certification lab report, photos of the inside of the equipment, and the user's manual.

Evaluation During Installation

The communications equipment resides inside the substation control house, i.e. the PowerLine Coordinators (quantity 2) and the PowerLine Gateways (quantity 2). The equipment panel was installed prior to EPRI site visit. This panel is labeled "PANEL 25 SmartValves and SmartBypass COMMUNICATIONS." Also, on this panel are a pair of SEL model 2730M managed Ethernet switches.

On the outside of the control house two antenna masts were mounted and four antennas had been added for the Smart Wires communications. Two 900 MHz band seven element Yagi type, directional antennas were mounted on one mast, and two 2.4 GHz directional antennas were mounted on the other. During the time of our observation technicians were working on installation of the RF transmission lines between Panel 25 and the antennas (Figure 4-4). The installation work appeared to be very professional and no issues were noted.



Figure 4-4
Pole Installation with antennas on control room [Source: Smart Wires]

The transmission line was not re-energized during the time that the EPRI Telecom SME was present. The indoor equipment (PowerLine Coordinator and PowerLine Gateway) was powered up and the technicians were working on configuration of the devices but did not advance to validating the installation or demonstrating functionality during the time that the EPRI Telecom SME was present. During the installation some simple tests on communications were performed though. Towards the end of the day the Smart Wires team powered up the indoor equipment,

including the Power Line Coordinator that communicates with the devices via the wireless links. One of the Smart Wires technicians used a spectrum analyzer to record the 900 MHz band before and after powering up the unit. The band was completely clear prior and after power up the technician was able to capture the FHSS signal from the unit.

Smart Wires produced a comprehensive report of the spectrum analyzer testing labeled "Central Hudson System Ohioville Substation RF Network Verification. [5]" This report contains screen shots of the spectrum analyzer readings and diagrams of where and how the measurements were recorded. The report also analyzes measured values against expected values. The report contains the statements below in the document's Section 3.3 Conclusion of Survey:

> The noise level is low and there is no significant interference in the 902-928 MHz band. The surrounding frequency outside the 902-928 MHz band does not show excessive and out of FCC regulation signals.
>
> The Smart Wires system uses a strong RF design with Frequency Hopping Spread Spectrum (FHSS) that will ensure good performance even in much noisier environment or in case other RF systems use the same frequency band.

These statements are consistent with the measurements; however, comments regarding the use of unlicensed frequency bands are provided in the "Observations and Conclusions."

Field Tests and Commissioning Plan June 2019

Smart Wires provided a document titled "Field Tests and Commissioning Plan [8]." The topic of Section 4 is E2E Communication Testing and Verification and includes detailed step by step procedures for each component of the communications system, wireless communications between the field devices, and indoor PowerLine Coordinator as well as the EMS SCADA integration. There is also a sub-section on "RF Network Verification" that aligns with the report described above that used a spectrum analyzer to characterize the RF environment on the two unlicensed frequency bands used by the system.

Section 3 of the document describes a handheld "Communication Test Unit (CTU)" and explains how it may be used to evaluate performance of the wireless communications before installing the field devices. . Since the equipment locations were selected prior to EPRIs visits to the Ohioville substation use of the CTU in the field was not observed. However, EPRI witnessed this device being used during the indoor benchtop demonstration on June 25, 2019.

Review and Evaluation During Field Demonstration

As described in Section 1, a field demonstration was conducted on June 25, 2019 with the objective to show how the commissioning process is performed and verify the functionality of the devices through operational testing.

The first part of the demonstration was re-initialization of the communication network. This was done to observe if the communications equipment powers up and connections between all components are established (all components join the network, re-authenticate, and communicate).

The configuration of the devices to match the physical components was completed by Smart Wires during the initial installation. During this demonstration, Smart Wires illustrated how this configuration is performed, showing how the field devices serial numbers are entered.

Smart Wires preconfigures the rest of the system in the factory. Hence, in the field the process is basically as follows: once devices are powered, they connect to the PowerLine Coordinator, when they receive a PowerLine Coordinator radio signal, they join it and wait for an authentication challenge. As part of the authentication process, they receive keys from PowerLine Coordinator. These keys are used to cryptographically protect all messages.

To simulate this process during the field demonstration, Smart Wires changed the network identifier to force all devices off the network, requiring them to repeat the process above.

Observation and Conclusions

The electric utility industry has a long history of use of FCC Part 15 wireless communications in the OT space. Several AMI (advanced meter infrastructure) vendors produce wireless mesh radios using the 900 MHz band and it is widely deployed in the U.S. In addition, multiple vendors manufacture Point to Multi-Point Part 15 radios that use the 900 MHz band, and these are widely deployed by utilities for SCADA and distribution field devices such as capacitor bank controllers and reclosers.

It is important however to note the conditions to which Part 15 devices are certified. These are required to be contained in the products user manuals and on product labels. Here is that compliance statement from the Smart Wires PowerLine Coordinator manual.

> This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at his own expense.

The FCC definition of a Part 15 Class A device is: “A digital device that is marketed for use in a commercial, industrial or business environment, exclusive of a device which is marketed for use by the general public or is intended to be used in the home.”

The FCC regulations require the use of one of two techniques to accomplish the goal of protection against harmful interference. These are Direct Sequence Spread Spectrum (DSSS) or Frequency Hopping Spread Spectrum (FHSS). The Smart Wires products use the later. Another relevant parameter in the regulations is limitation on the transmit power, with the general characterization of this being 1 Watt of RF transmitted power (excerpt below).

47CFR15.247(c)

> For systems using digital modulation in the 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz bands: 1 Watt. As an alternative to a peak power measurement, compliance with the one-Watt limit can be based on a measurement of the maximum conducted output power. Maximum Conducted Output Power is defined as the total transmit power delivered to all antennas and antenna elements averaged across all symbols in the

> signaling alphabet when the transmitter is operating at its maximum power control level. Power must be summed across all antennas and antenna elements. The average must not include any time intervals during which the transmitter is off or is transmitting at a reduced power level. If multiple modes of operation are possible (e.g., alternative modulation methods), the maximum conducted output power is the highest total transmit power occurring in any mode.

The result of these regulations is that Part 15 communications are susceptible to interference, whether unintentional or intentional (jamming).

It should also be noted that the neither the Field Tests and Commissioning Plan, nor the RF Network Verification report indicate the duration of the spectrum analyzer measurement. During the observation of the installation in February, the Smart Wires technician spectrum analyzer data collection appeared to be on the order of a few minutes in each location at the Ohioville substation. If the permanent installation at Hurley Ave 345 kV substation has a substantially longer distance from the devices to the antenna or if there are known interferers, then additional spectrum analyzer measurements over a longer duration could be a valuable exercise.

5
CYBERSECURITY

Introduction and Objective

The objective of the cyber security review was to evaluate and document potential methods of gaining unauthorized access and control of the Smart Wires SmartValve system. Both local and remote methods have been evaluated. In addition to evaluating potential attack methods, EPRI evaluated if the communications and control systems required for the project support NERC-CIP compliance, documenting and recommending security controls recommended for the installation and operation.

Approach

The approach followed in this section included the following activities:

- Analysis of potential methods of compromise after reviewing documentation provided by Smart Wires for the SmartValve product.
- Discussion of areas of concern with Smart Wires for further clarification beyond what was found in the documentation.
- Evaluation of the Smart Wires SmartValve product installation and documentation to determine alignment with NERC-CIP.
- Conclusion and observations.

Summary of the Information Received

The Communications and Control Overview presentation, on slide 17, summarizes most of the security features and where they are applicable, which is reproduced in Figure 5-1. At the request of the EPRI SMEs, Smart Wires provided a copy of the living NERC-CIP documentation outlining Smart Wires features and approach to helping utilities meet and show NERC-CIP compliance. Because this is a living document and changes are still ongoing, it is only generally referenced in this report. There were a few pieces of information requested to gain better insight into how one might compromise the Smart Wires system, but not provided by Smart Wires.

These include the independent penetration testing results and the corresponding corrective actions taken to correct the findings, the details about the proprietary protocol used for communication between the devices, and the testing results of the device-to-device communication and fault bypass timing.

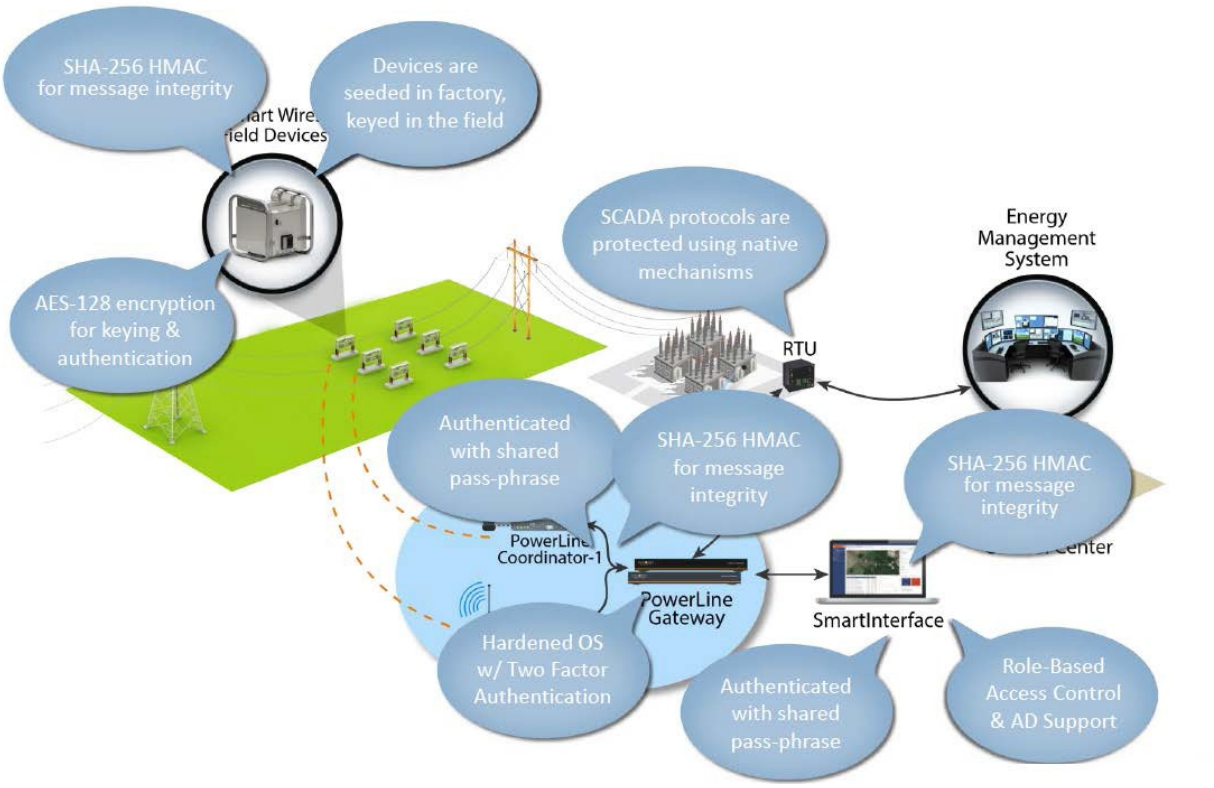


Figure 5-1
Security features of communication and control of SmartValve installation

After reviewing the documentation provided, EPRI submitted a set of questions on specific aspects for clarification. The questions and responses by Smart Wires are included in Appendix A for completeness.

Findings and Observation

Over the course of the time spent with the Smart Wires team and subsequent phone calls, there were numerous conversations about the operation of the system. One area of particular concern was the operation of the wireless communications. It was mentioned during the overview presentation that the SmartBypass units used the 2.4 GHz Inter-phase wireless communication to bypass any unfaulted phases during the event of a fault in less than 2 msn (Bypassing the faulted phase(s) happens locally in under 1 ms and does not require any wireless communications.) The product was not capable of inter-phase wireless communication at the time of installation and would require a software update to enable the feature. The Smart Bypass units would operate independently once the units were commissioned until said software update.

The wireless communication and operation of the SmartBypass units was questioned thoroughly through various channels. The questions intent was to make sure that the loss of the radio communications channel via jamming, radio failure or some other means would not adversely impact the grid during either normal operation or under several different fault conditions. In the event of this loss of communications, the devices will continue to operate under the last received parameters, bypass individually in the event of a fault affecting that phase.

In discussion with Smart Wires about the inter-phase radio communications while onsite for the installation, they mentioned the communications would be periodic and thus might take longer than the 2ms mentioned in the presentation. The delay presents a concern as an attack surface that could potentially impact operations. The impact of a delay upon the power system is described in further detail in the Power System Impact section.

Compromising the system and potentially impacting the operation of the energy delivery systems through means of the wireless channel going back to the substation was evaluated. Compromise of this channel is a low probability and low or no potential impact. In questioning it was stated that there were no capabilities for command and control to be asserted from the wireless channel into the PowerLine Coordinators and PowerLine Gateway. The method of further isolating the PowerLine Gateway from the SCADA through the RTU helps insure communications are limited to operating as designed. Smart Wires addressed this in more detail in their NERC-CIP documentation in multiple places.

Compromising the system through physical access was evaluated as was compromising the system through directly interacting with the system. Examples of this would be technicians performing software updates or physically tampering with the hardware. Protection against compromise through corrupted software packages is accomplished through the cryptographic protection and verification of the signed software packages. Unsigned packages or those that fail the cryptographic integrity tests are discarded. There are sensors to detect and alert on physical tampering that can be configured when needed or as desired. Smart Wires describes their protections throughout their NERC-CIP documentation, but specifically addresses much of this in their sections on CIP 6-6, CIP 7-6 and CIP 14-2.

The SmartInterface presents the highest risk of compromise to the system. From the SmartInterface the attacker would have the ability to control and reprogram the operation of the devices. A set of compromised credentials or other attack avenues could be used to gain access to the control of the system this way. This risk can be easily mitigated by not having the SmartInterface running and accessible. Without SmartInterface running, the control of the system is entirely dependent upon communications from the EMS over the SCADA network. Control of the system in the absence of SmartInterface is subject to the same security concerns of any other device operated by way of the RTU.

It should be noted that the SmartInterface is primarily used for commissioning or to acquire system diagnostics and therefore is typically not being used during normal operation. When being used, it has full role-based access controls, Central Hudson can choose to issue only limited-access credentials. While use of the SmartInterface is unavoidable during the commissioning and initial setup of the system, it is recommended that the SmartInterface be disabled after EMS control of the product is established.

Smart Wires developed documentation describing how they address potential NERC-CIP concerns. Included in the documentation is a detailed description of how Smart Wires performed their comprehensive evaluation and steps taken to help utilities meet potential NERC-CIP concerns.

Smart Wires has designed their system, so they believe they reside outside the electronic security perimeter (ESP) for most BES deployments and thus not viewed as a BES cyber asset. It should be noted that BES Cyber Assets are not necessarily within the ESP. In their NERC-CIP

documentation it is described in detail how they determined this evaluation and the steps taken to help utilities meet any potential NERC-CIP concerns.

In a phone conversation between EPRI Cyber Security and Smart Wires, EPRI mentioned that this could be a liberal interpretation of where and how they apply the rules. EPRI brought up the point that system distinction under NERC-CIP is determined by impact of the system, not the functionality of the system. The question was then raised by EPRI "What was being done to address concerns or answer questions surrounding NERC-CIP for the customer or auditor who views NERC-CIP conservatively and thereby views the Smart Wires product as a BES Cyber asset?" It was noted that much of our discussion revolved around the product being installed at a low impact substation and questioned if NERC-CIP considerations had been evaluated for the product for medium and high impact substations. Specifically, concerns were raised about NERC-CIP 5, 6, 7 10 and 13 for medium and high impact substations/control schemes and how it would differ when compared with their current position. Since the phone conversation, Smart Wires has further developed their NERC-CIP documentation to address the concerns that were raised during the call.

The security controls needed to make sure that the command and control of the product meets NERC-CIP compliance will depend upon if Central Hudson takes a more liberal or conservative view of the product. It is recommended that Central Hudson decides on how the product is viewed and then work through Smart Wires NERC-CIP documentation raising any potential concerns with Smart Wires. The security controls, such as firewall placement, will change dependent upon the stance taken. While use of the SmartInterface is likely unavoidable during the commissioning and initial setup of the system, it is recommended that the SmartInterface be disabled after EMS control of the product is established. In conclusion, Smart Wires has put a lot of thought into their security architecture, hardware and software development, and resources into testing the product to limit the attack surfaces and vectors. The independent penetration testing and liberal use of cryptographic integrity checks is a good step towards making sure the system is as secure as it can be without adversely impacting performance or operation. Any concerns or gaps found apparent in the penetration testing results not already addressed should have a risk analysis performed. Since these results were not available to EPRI it is recommended that Central Hudson further evaluate the system and decide which risks are acceptable. It is worthwhile to emphasize that all risk cannot be eliminated without adversely impacting operations of the product. How close product alignment is with NERC-CIP is dependent upon how the product is assessed by Central Hudson. There may still need to be some work needed to NERC-CIP documentation provided by Smart Wires to satisfy Central Hudson's regulatory concerns.

6
PROTECTION IMPACT

Introduction and Objective

The SmartValve device installed at Central Hudsdon's Ohioville substation is designed to generate a voltage of up to 566 V AC across its terminals. Injecting such a voltage onto a current-carrying conductor results in a series reactance, thus either increasing or decreasing the overall series impedance of the circuit. The magnitude of the injected impedance is a function of the injected voltage, which can be dynamically controlled, and the magnitude of the current carried by the conductor, which is primarily dependent on the operating conditions of the grid and the reactance of the SmartValve itself. Thus, there is a non-linear relationship between injected voltage and reactance across the SmartValve terminals.

When attached to a transmission line conductor, the inductive or capacitive reactance of the SmartValve will exhibit a current-reactance characteristic similar to that shown in Figure 6-1. The exact values represented in Figure 6-1 correspond with the capabilities of the devices installed at Central Hudson's Ohioville Substation. Values will differ for other SmartValve models. The series reactance can be seen to taper off as the magnitude of the current flow increases up to its rated current. Beyond the rated current, the SmartValve has a maximum 2-hour emergency current - in the case of the Ohioville units, 990 A. During emergency conditions, the SmartValve can inject its rated voltage provided the maximum emergency current and duration are not exceeded. If exceeded, the SmartValve will automatically bypass. Higher emergency current ratings may be possible depending on duration and environmental operation conditions. The bypass circuit is shown in Figure 6-2. The control system permits the user to configure the bypass action to occur at lower current magnitudes.

Bypass of the SmartValve and Grid Protection

For three-phase overcurrent conditions the SmartValve units on all three phases will activate. For single and two-phase faults the SmartValve on the faulted phase(s) will bypass and also command the SmartValve units on the unfaulted phases to bypass within 2 ms. With this performance the impact of the series reactance on distance protection fault detection algorithms should be minimized.

The objective of the protection impact tests is to assess the actual performance of the SmartValve in response to nearby faults and other transient disturbances. If the SmartValve bypasses on the faulted phase within the design time of 1 ms and unfaulted phases within the design time of 2 ms then it will be deemed to have passed.

The advertised performance suggests that the bypass switch will activate within 2 ms of an overcurrent condition being detected. If this performance can be achieved, then it is not envisioned that the SmartValve will have limited impact on the performance of conventional protection systems. To fully determine if this performance was achieved, measurements from

protection relays and digital fault recorders would be required. Unfortunately, there were no system disturbances (nearby transmission faults etc.) during the test period which would enable evaluation.

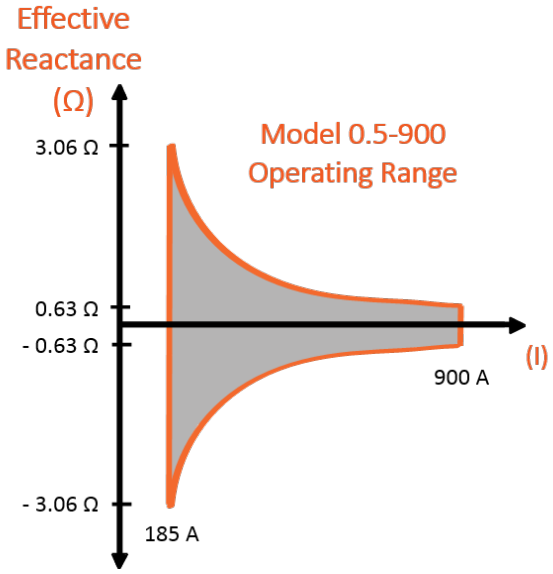


Figure 6-1
SmartValve model 0.5-900 injection characteristic

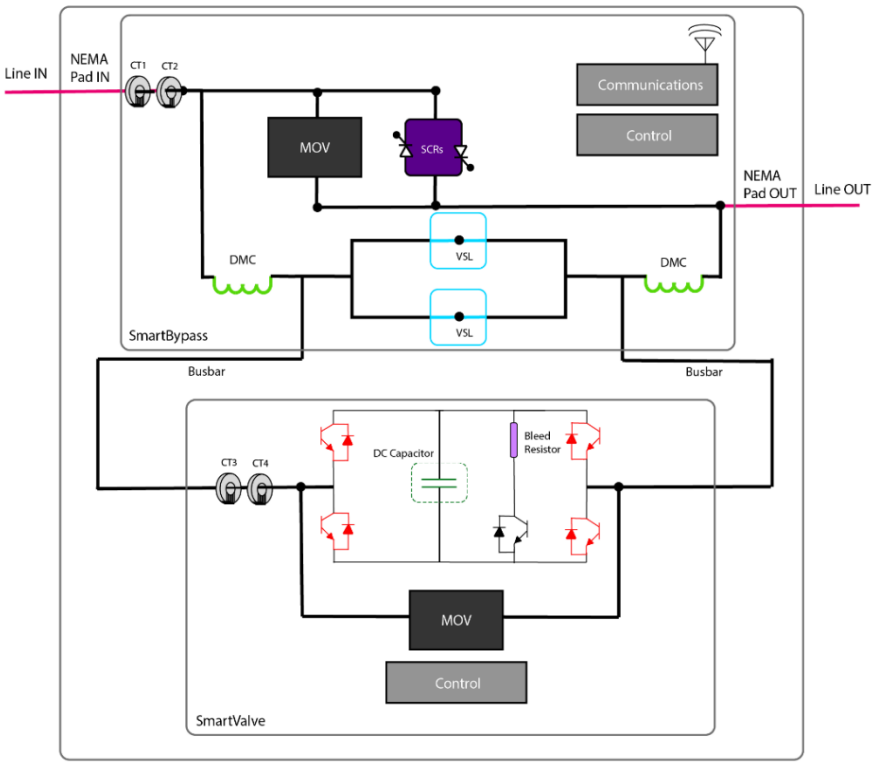


Figure 6-2
SmartValve and SmartBypass system diagram

A full protection study was performed by Schweitzer Engineering Labs (SEL) for the SmartValve installation planned for Central Hudson's Leeds Hurley substation. SEL ES simulated a wide range of internal and external faults using predetermined system conditions and test batches agreed upon with Smart Wires, Central Hudson, and National Grid to study the impact of the SmartValve deployment on the protective elements used to trip the SEL and GE relays. The study included high impedance faults in the 10 to 50 ohm range. The maximum observed distance elements overreach under capacitive compensation was 5-7%, while the maximum observed underreach under inductive compensation was 5%. This performance is contingent on the SmartValve bypassing within 2ms of a power system fault occurring.

While the SmartValve and SmartBypass will have undergone extensive lab-testing to ensure secure and reliable operation, it is still prudent to examine how the failure of the SmartValve and SmartBypass could impact protection performance. The main failure modes of the SmartValve and SmartBypass devices which could impact protection performance include:

1. Failure to bypass on the faulted phase during a fault
2. Failure to bypass on the unfaulted phase(s) during a single or two-phase fault
3. Different control modes or status across the three phases without fault

Failure to Bypass on the Faulted Phase During a Fault

Should the SmartBypass fail to bypass the associated SmartValve(s) during a fault then the main impact will be on impedance protection relays. Such relays continuously measure voltages and currents on the protected line; should a fault occur on the protected line, the measured impedance will fall below a critical value resulting in the relay issuing a trip command to local circuit breaker(s). Multiple impedance zones are used to enable the relay to also detect faults on nearby lines and provide remote backup protection.

Should the SmartValve fail to bypass, then the line impedance will be larger than expected, but with appropriate setting calculation and design, the relay should still be capable of detecting the fault and tripping. The likelihood of a bypass failure is low due to redundancy of components in the SmartValve. Where pilot systems are used such as directional comparison blocking (DCB) or permissive over-reach transfer trip (POTT), it should usually be possible to extend the fault detection zones to encompass both line impedance and the additional impedance of the SmartValve. In such a case the fault clearance time should still be within the normal expected range. Where pilot protection schemes are not used or the pilot protection scheme is out of service, then the relay should still detect the fault, although the trip time may be delayed.

In the event of a high-resistance ground fault, the fault current may be very low and in some cases the fault current could be below the bypass threshold of the SmartValve. Where many SmartValve units are in series this could be particularly true. This is not foreseen to be an issue on the transmission line under testing as the SmartValve only decrease the line impedance by a small quantity and the fault current levels at each end of the line are relatively strong.

A full protection coordination study would be necessary to determine if or when such an issue is a credible risk or not.

Failure to Bypass on the Unfaulted Phase(s) During a Fault

In this case, the SmartValve correctly bypasses on the faulted phase(s), but due to communications system failure or some other system failure, the SmartValve units on the unfaulted phases do not bypass. The impact will be less severe than that of the previous case and in most cases should not impact impedance protection performance, but the increased impedance could impact impedance calculation in certain cases. Due to the small size of the impedance injected in this project, no impact is foreseen. A full protection coordination study would be necessary to determine if or when such an issue is a credible risk or not.

Results from studies performed by Schweitzer indicate that the bypass of the phases unaffected by the fault was not necessary for proper relay operation.

Different Control Modes or Operating Status Between Phases

During normal operations it may be necessary for the grid operator to change the SmartValve control mode. Should such a command fail to reach the SmartValve units on all three phases, they could operate in an unbalanced manner. For example, the SmartValve on phases A and B inject reactance while the SmartValve on phase C does not. This would result in unbalanced impedance and the flow of unbalanced (zero and negative sequence) current. If this unbalanced current was sufficiently large it could exceed a ground overcurrent protection setting.

This failure mode is minimized by the system design. The system acknowledges commands and retries messages. If interphase balancing is enabled, groups of SmartValve devices will drop out of injection if all units in a group fail to go into injection.

Where directional comparison blocking or directional comparison ground fault pilot protection schemes are used, such unbalance current is unlikely to trigger protection operation. The relays at each end of the line should have similar settings and should be able to correctly determine that no fault exists on the line.

A full protection coordination study would be necessary to determine if or when such an issue is a credible risk or not.

Approach

In order to assess the performance, the use of protection relay and digital fault recorder measurements from nearby system disturbances are required.

In each case the records will be examined to determine:

1. Did the fault current exceed the bypass threshold of the SmartBypass
2. Did the SmartBypass switch close within 1ms on the faulted phase
3. Did the SmartBypass switch close within 2ms on the unfaulted phases
4. Did the SmartBypass slow down fault detection time or in any material way impact protection performance

Summary of the Information Received

As part of the preparatory work the following information was requested and received:

1. Line impedance information
2. SmartBypass design and specification
3. Schweitzer Report
4. DFR and relay event records.

Observation and Conclusions

While no major impact on protection performance is envisioned for this line, it was not possible to validate these assumptions using field measurements. Where a SmartValve fleet is installed with high percentage compensation, the effects could be more pronounced. Protection coordination studies can be used to determine the potential impact. A comprehensive protection study was completed for Central Hudson by SEL with results showing minimal impact on existing protection, assuming the SmartValves perform as expected.

7
POWER SYSTEM IMPACT

Introduction

The objective of this part of the evaluation was simply to verify that changes in the devices injection mode effectively produce a change in the line current. That is, EPRI sought to observe an increase in line current when the devices enter into capacitive injection mode, and conversely, observe a decrease in line current when the devices enter inductive control mode.

The impact on line current depends not only on the series voltage injected by the devices but also on the characteristics of the network and operating conditions. Therefore, the demonstration was not intended to verify a certain level of line current changes but rather a qualitative observation of current variations.

Also, general observations and comments are provided about reliability implications that should be considered in the technical evaluation of transmission solutions using SmartValve devices.

Review and Evaluation During Field Demonstration

It was described in Section 1 that the field demonstration conducted in June 2019 included verification of the following: a) Re-initialization of the communication network, b) Injection test via Human Machine Interface (HMI), and c) Injection test via SCADA. A description of the communication re-initialization results was provided in Section 4. This section addresses the other two items, as described next:

Injection Test Procedure

Injection Test Through Human Machine Interface (HMI)

This test was performed to verify that the devices were able to be controlled locally from the substation through the SmartInterface. It included verification of signals sent from the HMI (substation-based SmartInterface), the devices' response, and the HMI verification of response.

Once the system was energized, Smart Wires proceeded to inject various levels of series voltage and maintained the injection for a few minutes to allow line current to settle and give enough time for measurement and observation. The general injection testing procedure is described in the Field Tests and Commissioning Plan, June 2019 [8]. In this case, only voltage injection test was performed.

The verification process and acceptance criteria are as follow:

1. Verify through the SmartInterface that:
   - All three units inject at the configured voltage
   - No alarms present

- All icons indicate proper mode of operation

2. Verify the following at System Operator:
   - No alarms are triggered
   - Injected voltage in percentage
   - Phase A,B,C compensation values match the local interface
   - Phase A,B,C SmartBypass Mode
   - Phase A,B,C SmartValve Mode
   - All units correctly return to Monitoring mode when no injection is applied

Injection Test Through SCADA

This test was intended to verify that the devices were able to be controlled remotely from the SCADA/EMS. In order to visualize the command entered in the SCADA, a replica of screen was projected in the wall of the substation control room, as shown in Figure 7-1 and Figure 7-2. Changes in relevant variables are verified with the substation equipment and SmartInterface, as well as with measurement logs. In this way, it is possible to validate that the injection status and injection level change, that the devices on the circuit go into injection, and that a change in current flow is observed.

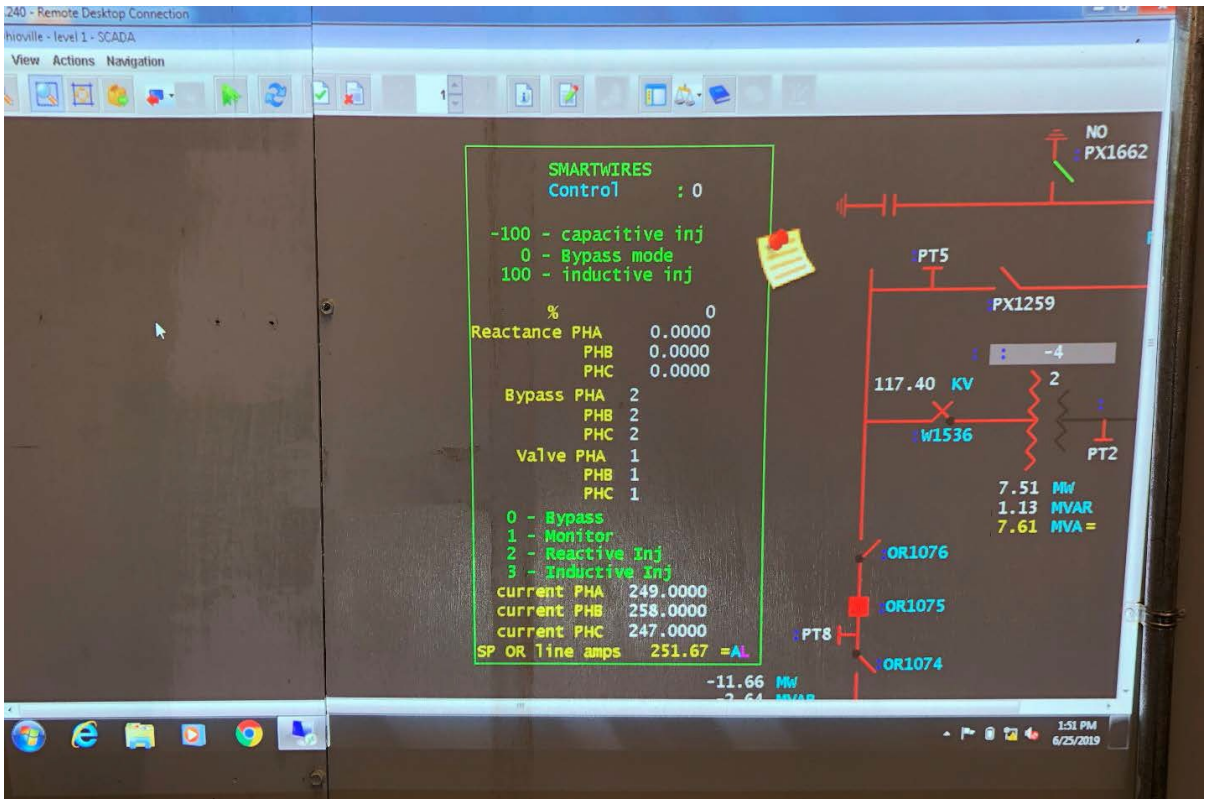


Figure 7-1
Replica of SCADA screen projected onto the wall of the substation control room – Monitoring mode

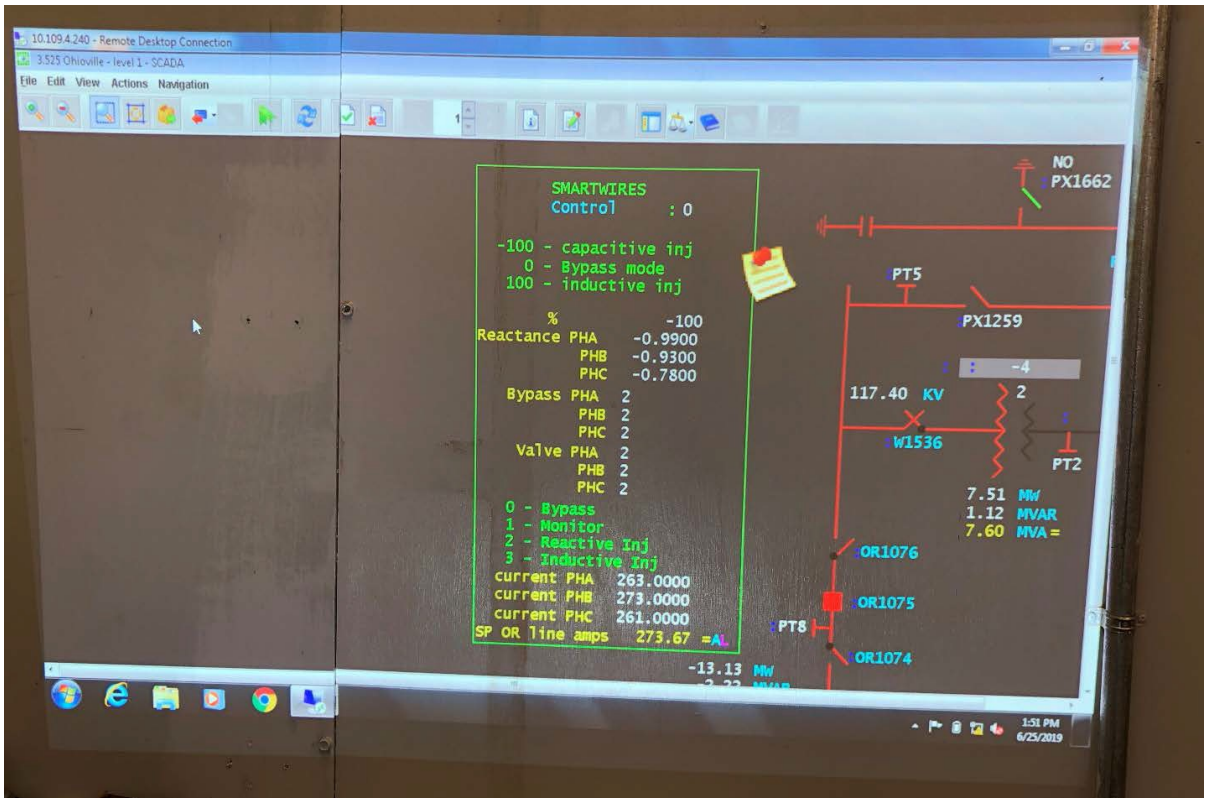


Figure 7-2
Replica of SCADA screen projected onto the wall of the substation control room – Capacitive injection mode (500 V)

Test Results

Central Hudson and EPRI personnel confirmed the results through visual verification of the HMI screen and measurement instrumentation. Smart Wires also provided a copy of measurement logs. Table 7-1 summarizes the tests performed and shows the steady-state value of the relevant variables measured during the test, in particular; the phase current and the three-phase power flow from both ends of the line where the SmartValve units are connected. Figure 7-3 is a plot of the phase current profile during the execution of the injection test.

Table 7-1
Injection test results

Injection level	Mode	Line Current [A]			Data Source	Power Flow				Data Source
		Phase 1	Phase 2	Phase 3		PX line [MW]	PX line [MVar]	OR line [MW]	OR line [MVar]	
500 V	Capacitive	265	276	265	HMI	-3	1.7	-12.1	-2.7	Subs. Equip.
0 V	Monitoring	248	259	243	HMI	-4.3	2	-10.9	-3	Subs. Equip.
250 V	Capacitive	256	267	256	HMI	-3	1.9	-12.5	-2.6	Subs. Equip.
250 V	Inductive	233	243	233	HMI	-4.5	2	-10.8	-3.1	Subs. Equip.
500 V	Inductive	224	232	224	HMI	-5.8	2	-9.4	-3.1	Subs. Equip.
0 V	Monitoring	247	256	246	EMS					
500 V	Capacitive	268	278	266	EMS					

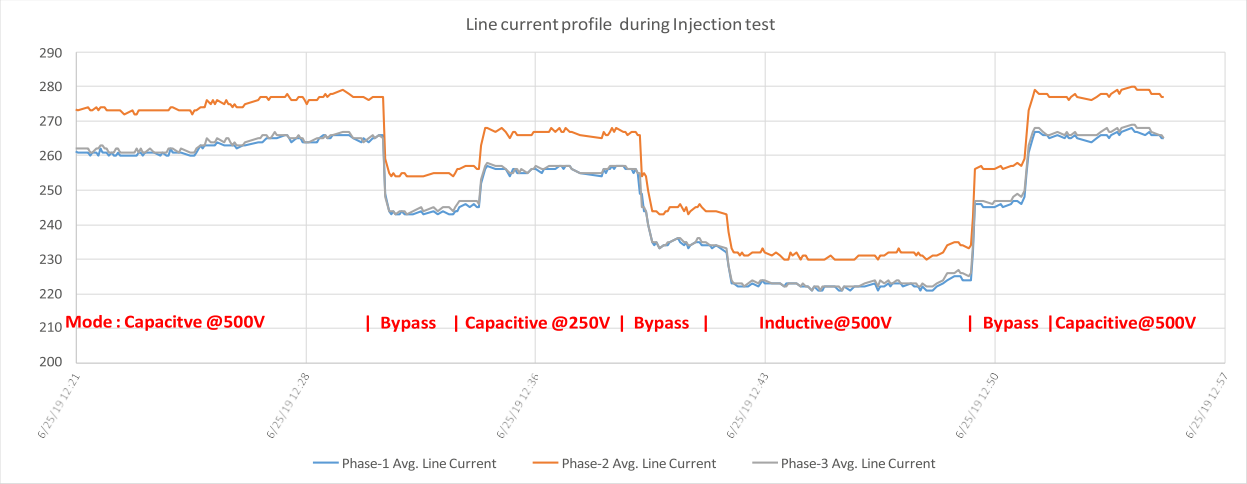


Figure 7-3
Line current variation during injection test

The results of the injection test show that the line current effectively changed according to the series voltage injected by the SmartValve units. It is observed that the line current increases as the series voltage in capacitive mode is increased from 0 V, to 250 V and to 500 V, and conversely, how the line current reduces as the devices enter inductive mode.

Observation about Potential Impact to the System

It was pointed out in Sections 4 and 5 that one of the features of SmartValve installations that may pose vulnerability to the system is the wireless communications. It is necessary to evaluate the potential impact, and the severity, that the loss of the radio communications channel via jamming, radio failure or some other means may have on the system either at normal operation or under several different fault conditions.

In general terms, the question to answer would be “What is the implication of loss of the radio communication channel of the SmartValve/Smart Bypass devices to system operation?” Like with any other device or control equipment, there are several failure modes that need to be considered in risk evaluation to respond to this question, and SmartValve technology is not different than other equipment in that regard. However, in this case the wireless communication may add another layer of potential issues, mainly because wireless communication may not operate properly even if there is no equipment malfunction or failure. As explained before, the use of unlicensed bands or any other RF is susceptible to interference, whether unintentional or intentional (jamming), which may cause delays or abnormal communication. To conceptually understand the potential impact to system operation, one can identify how the communication failure may impact the various features of attributes that a control system or wide area protection scheme using SmartValve devices would need to fulfill. These main attributes are the following:

- Dependability: is a measure of certainty to operate when required.
- Security: is a measure of certainty that the scheme will not operate when not required.
- Selectivity: ability to affect the least amount of action when performing its intended function.

- Robustness: ability to work correctly over the full range of expected steady state and dynamic system conditions.
- Adaptability: ability to be updated with minor changes in order to accommodate to the changes and expansion of the power system.

Among these attributes, dependability and security will be the ones mainly affected by wireless communication issues. The other attributes are mostly related with the control function design and settings.

The importance of communication delays or failure in the dependability characteristics of the control scheme will depend upon the purpose of the control and characteristics of the control. To illustrate the concept, consider the following control modes/schemes:

- Current control: As described in Section 2, in this control method the SmartValve fleet actively regulates the magnitude of the line current through the facility to stay below a given level or equal a given level (current setpoint). If the operator changes the current setpoint remotely from the control room, the wireless network is used to transmit the control signal to the devices in the field. However, once the setpoint is stablished, the deployment operates autonomously. If the line current varies due to, either normal changes in the network operating conditions or a result of a contingency, the devices will adjust the injected voltage to maintain the current value to the setpoint. Such control is self-contained within the device, thereby eliminating the risk of failure in control action due to loss of communications during normal operations or contingencies.
- Injection at a fixed voltage or injection at a fixed reactance: Similar to the current control method, once the setpoint is setup, the control of the SmartValve fleet is performed locally without any dependency on wireless network. Therefore, the dependability of this type of control is not affected by the wireless communication, other than the initial setpoint.
- Centralized post-contingency control scheme: In some applications, it may be desirable to use the SmartValve fleet on one or more transmission lines as part of a centralized protection scheme intended to relieve overloads under critical contingencies (it could be classified in some case as a special protection scheme or remedial action scheme). A centralized control system uses measurement from devices placed in various locations in the transmission system to detect abnormal conditions on the power grid and automatically select and initiate the appropriate control actions. In this case, the central controller will determine the voltage or reactance injection at each SmartValve deployment necessary to mitigate the line overloads and it will send the control commands to the devices. These command and control signals are sent through the communication infrastructure, which in this case includes the wireless communication network. Therefore, in this particular application, the wireless communication may pose a security risk. Indeed, a delay or failure in the control action may have severe impacts on operation security such as equipment damage, cascading outage, or other degrading effect to the transmission network integrity due to actuation of backup protection or other controls.

In order to realize the actual risks, a detailed evaluation of the control scheme attributes will need to be performed to assess the potential impacts of misoperation or failure to the system, and eventually design the necessary mitigation measures. The analysis should be conducted through

extensive simulation studies systematically covering the whole range of anticipated system operating conditions and contingency events.

Generally, to enhance dependability of critical controls or protection schemes, they are designed with sufficient redundancy of control actions such that a scheme can perform its intended function while itself experiencing a malfunction of any component. This redundancy is normally provided by duplication, so that single point vulnerability is avoided. Smart Wires performs thorough testing to verify reliable radio communication in the substation.

8
CONCLUSIONS

Observations from EPRI's Work

In this project EPRI observed Central Hudson's pilot installation of SmartValve and SmartBypass units with the objective to evaluate the functioning of the technology, identify and recommend areas for improvement and areas for further analysis and investigation, and summarize findings and EPRI's experience into a technical document.

The pilot installation consisted of a small deployment of three SmartValve units and the corresponding SmartBypass units at a 115 kV line that runs from the Sturgeon Pool substation to the Ohioville substation. The intention of this small deployment was for Central Hudson to gain experience with various aspects of the technology.

EPRI observation and evaluation work focused on the following key areas: installation process, communication and controls, cybersecurity, impact on protections, and impact on power system operations and reliability. The work performed by EPRI included two site visits. The first visit was in February 2019 during the installation of the Smart Valve and Smart Bypass devices at Ohioville Substation. The second visit took place on June 25, 2019. The objective of the field demonstration was to show the operation of the devices and provide explanation about the commissioning process followed by Smart Wires for illustration purposes.

The following are the main observations and conclusions from EPRI work:

- The initial installation performed on February 2019 was smooth with no incidents. No special trucks were necessary during the installation; the crews used their usual work trucks, tools and equipment. During the installation, a few changes and improvements were implemented to solve a few issues with insulation, pole stability, and to protect wildlife.
- Smart Wires uses 2.4 GHz for inter-phase communication between the SmartBypass devices, and 900 MHz is used between the PowerLine Coordinator and the SmartBypass. Wireless communications on these two spectrum bands are allowed by the FCC under 47 CFR Part15 regulation under an unlicensed scheme and are secondary to use by ISM devices (industrial, scientific, and medical) under 47 CFR Part 18 rules. The use of wireless communications in these bands are susceptible to interference, whether unintentional or intentional (jamming). Smart Wires explained that the communications between the PowerLine Coordinator and the SmartBypass/SmartValve field units is not critical to the moment to moment functionality of the system but is necessary to change settings or query status. Nevertheless, it is necessary to evaluate the impact that loss communication may have in system operation security and how appropriate settings and configuration of the Smart Wires solution may mitigate that impact.
- Like in any other control devices, equipment failure or malfunction may adversely impact system operations under normal or contingency conditions. The potential impacts need to be

assessed through a comprehensive analysis considering many possible failure modes. In that regard, SmartValve and SmartBypass units are not different from other equipment.

However, RF communications adds another potential risk because communication delays or disruptions may occur due to external causes. Central Hudson will need to evaluate how autonomous system behavior can offset or reduce that risk.

- It could be said that the larger deployment planned for the 345 kV Leeds-Hurley Avenue transmission line would be less severely affected by wireless communication issues because the intention is to vary voltage injection in real-time to maintain a fixed apparent reactance (to deliver equivalent of 21% series compensation). However, the distance between the control house antenna and the field devices should be assessed at Hurley Avenue 345 kV Substation and an unobstructed direct line of sight RF path should be engineered to maximize the receive signal strength an and minimize susceptibility to external interference. Nonetheless, the risks of communication delays or failure should be carefully assessed. Smart Wires utilized a communication test unit (CTU) to assess the reliability of the communication path prior to installation at Ohioville; the same should be done for Leeds-Hurley.
- Regarding cyber security, EPRI observed that Smart Wires has put a lot of thought into their security architecture, hardware & software development and resources into testing the product to limit the attack surfaces and vectors. However, additional work may need to be done by Smart Wires to satisfy all Central Hudson's regulatory concerns. Smart Wires has updated their documentation to address raised NERC CIP regulatory interpretation concerns, but it has not been reviewed in depth to determine if any concerns still exist. As with any product, changes to the design should result in a new penetration test being performed on the updated product. No penetration results were shared with EPRI, so all findings were only based on statements in the available documentation, from observations during the initial installation, and through conversations with the vendor. According to Smart Wires, in testing to-date, while there have been implementation findings that have required mitigation, there have been no security flaws found in the system architecture or the communication protocols. Any unaddressed vulnerabilities discovered in Smart Wires undisclosed penetration testing results that exist in the Central Hudson deployment architecture should be disclosed by Smart Wires to Central Hudson for review and risk assessment.
- A desktop review of the equipment and performance found no significant impact on the performance of nearby protection assuming that the SmartBypass units perform as advertised. Measurements were not available from digital fault recorders or protection relays in order to fully validate performance.
- During the demonstration test EPRI observed that injection of series voltage through SmartValve units effectively changed power flow of the transmission line. The devices responded through the control command both locally through the SmartInterface, and remotely from SCADA/EMS. The only control mode tested was the injection of a fixed voltage. The other control modes supported by SmartValve units were not enabled in this pilot installation.

Pilot Learnings

During the field demonstration on June 25, 2019, Smart Wires described several issues that they had faced after the installation in February 2019, and the approach taken to solve them. A table with detailed description of the issues and their status was included in the presentation given at site visit in June. Nine issues ranging from “small” to “medium” type were described, all of them reported as resolved.

There was one additional issue report as pending. The SmartValve on Phase 3 detects an anomaly and protects itself by switching into monitoring mode as designed. The device automatically re-injects in roughly 1 minute.

It was found out that this abnormal actuation of the bypass protection occurs when the capacitor bank located in the Ohioville substation switches into service. The exact cause had not been established at the time of the site visit, but it was suspected to be the effect of the high frequency voltage signal. Smart Wires indicated that after root cause analysis is complete corrective actions would be implemented, and the process would be modified to ensure a similar issue does not occur in the future.

Smart Wires and Central Hudson then informed EPRI that the issue was solved. The description provided by Smart Wires indicated that the observed behavior was further understood via data which showed that certain transmission operator-initiated switching events (such as switching shunt capacitor banks) resulted in some of the SmartBypass devices entering Monitoring Mode due to a traveling wave and returning to Injection Mode within 1 minute. To prevent traveling waves from affecting the SmartBypass operation, Smart Wires proposed adding a filter across the SmartBypass terminals to provide a low impedance path for the traveling waves to pass without entering the SmartBypass. Smart Wires has also added a fast transient response capabilities that offers re-injection in less than 1 second for certain types of faults.

Other Observations

As described above, during the site visit in June 2019, Smart Wires gave a demonstration of the commissioning process and tests. Most of the configuration work is done at the factory before shipping the devices, hence the commissioning process in the field is quite simple. The factory-based commissioning work is mainly manual, but it was explained that they are working on automating the entire process.

One important aspect discussed at the meeting is about the process to update the system software. The software can be updated while the devices are in operation, meaning that it is not necessary to disable/bypass them. However, the utility may want to do it for safety reasons, because the devices are not visible during the updating process, and consequently the operator will lose awareness on the devices status and functioning. In later communication Smart Wires indicated that they separated the process of transferring new firmware to the devices from the process of activating that firmware. This allows the transfer process (which requires more time) to be done while the devices are in operation. Smart Wires recommends activating the firmware only when the devices are not injecting. It might be important to consider the operational mechanics of firmware upgrades on large SmartValve deployments such as the 345 kV Leeds-Hurley Avenue line project.

It would be advisable to evaluate the risks of control changes while the software is being updated, and eventually design and implement a procedure to perform the software update.

9
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[4] Calculation Package - Central Hudson Gas & Electric Corporation SmartValve and SmartBypass Pilot Project

[5] Central Hudson System Ohioville Substation RF Network Verification, May 24, 2019 (report)

[6] Power System Protection Study - RTDS Tests on Smart Wires Products, DNV GL Document No.: 10058667-R-01. Issue Date: 30 April 2018 (Report)

[7] Smart Wires, Project Update. May 23, 2019

[8] Smart Wires, Field Tests and Commissioning Plan. June 2019

[9] Smart Wires, Site Visit Presentation, June 25, 2019.

A
RESPONSES TO EPRI QUESTIONS

1. What is the process involved in updating the components (gateways, coordinators, bypass and valves)?

   Smart Wires response: The Smart Wires solution allows all devices (PowerLine Coordinators, PowerLine Gateways, SmartBypasses and SmartValves) to be upgraded over the air. This is done using the SmartInterface application, with the exception of the PowerLine Gateway which uses a different update tool. The circuit does not need to be taken out of service to install an update, but Smart Wires does require that devices be in monitoring mode (not actively injecting) when the update is applied.

2. What steps are taken to insure that all firmware/software updates are uncompromised? (my understanding is signed).

   Smart Wires response: Yes, all firmware images are signed and are verified before they are accepted by the system. In addition to the firmware signature verification, when firmware images are transferred all of the blocks are protected with keyed-hashes. Each block is verified and the reassembled image is cryptographically verified as well.

3. What steps and precautions are taken to insure the process stays within regulatory compliance?

   Smart Wires response: The system goes through all required testing to be FCC certified and Radio Equipment Directive (RED) compliant for Europe. Updates which affect RF communications may be handled as an FCC permissive change or may require retesting depending on the circumstances. In most cases, retesting is not required as it is only application messages which are being changed.

4. Is the communication between a bypass and its team members periodic, and if so what is the period of communications?

   Smart Wires response: In order to speed-up responsiveness, messages are sent periodically, not on a triggered basis, with the current status of the device at the time of the transmission.

   Each SmartBypass can communicate with up to five SmartValves over a fiber-optic link. SmartBypasses are assigned to groups in order to communicate status to the respective other two peers on neighboring phases. A 2.4-GHz link is used between members of a group for the interphase status information.

   In the current hardware, messages are sent every 2.5 milliseconds, with each of the three units in a group transmitting in rotation. The 2.4-GHz link uses a frequency-hopping spread-spectrum physical layer. Further, the actual deployed design ensures that neighboring groups are on different hopping patterns to minimize contention and collisions.

5. Is the communication also enabled by event triggers so a fault would trigger an immediate communication?

   Smart Wires response: As noted above the communication is periodic. When a fault occurs on one phase, the response time can vary depending on which phase the fault occurred on and which unit is currently transmitting. Bypass will occur within approximately 3 msec with the current configuration for the Central Hudson pilot at the Ohioville substation. Please note that if the neighboring phases are faulted too, the local fast fault detection of the SmartBypass will activate, causing the device to bypass. In this case the 2.4 GHz link is not involved. The link is only used to ensure balanced behavior between phases. Improvements to our control board hardware to allow us to exchange these messages even faster are being implemented so that the total time from fault inception on any phase to all three phases being bypassed will be 2 msec or less for the Leeds-Hurley Installation.

6. Has the timing between a fault event trigger and the time the secondary SmartBypass bypasses been tested in a real world environment, and if so what were the results?

   Smart Wires response: Yes, the timing has been verified it using a two-step methodology. First, the single phase fault detection and bypass within 1 msec or less has been verified up to 63 kA RMS in outside test labs in an electrically noisy environment. The interphase communication was verified separately using our automated test systems. The results of these two tests support the bypass response as documented above. A variety of simulations have been run on how the system will behave with the interphase balancing feature enabled.

7. Are you worried that channel congestion, either from a large number of devices or external noise, during a fault event could delay the bypass process?

   Smart Wires response: Yes, the crypto-overhead can be a concern on fast messages like the ones used in the 2.4 GHz link. Cryptographic protection is used in that link using keyed hashes. To manage the overhead, the number of hash iterations was reduced. While this makes a potential brute force attempt to spoof a packet easier, every message has a monotonically increasing counter. Late messages are simply discarded. Given the constant stream of messages every 2-3 ms, the window for producing a correct spoofed message is still infinitesimal relative to the computational burden of a brute force attack. This does not create a meaningful reduction in security, as rate of communication effectively compensates for the reduced number of rounds.

8. Have any simulations been run to identify how tripping would be impacted in a situation where the communications channel used to bypass the other phases is being actively jammed?

   Smart Wires response: Yes, protection impact studies have been conducted to determine the impact when one phase is bypassed due to a fault, but the interphase communication is disabled so the other phases do not bypass. In the original protection impact study conducted by Schweitzer Engineering Laboratories (SEL), Inc. for the Central Hudson Leeds Hurley project, the interphase communication feature was not implemented and for single line to ground faults, only the affected phase was bypassed. That study showed that the relays still operated correctly and the fault was cleared. The most recent study protection study conducted by SEL for the Central Hudson Leeds Hurley project conducted tests to see of the interphase communication would reduce overreach. For capacitive compensation cases where

overreach was observed during faults, there was no difference in the protection response with interphase communication enabled verses disabled. It should be noted that the amount of over-reach observed was 3 – 4% maximum in the most recent study and will be compensated for with adjustment of the existing distance relays.

9. What is the maximum amount of time you would expect to pass before all SmartBypass units in the planned Hurley deployment were in bypass mode in the event of a high impedance fault?

   Smart Wires response: The maximum amount of time is 2 msec for the Leeds-Hurley deployment. The SmartBypass has been verified to respond to high resistance to ground faults up to 150 ohms under various operating conditions within 1 msec in a general protection study conducted by DNV-GL. Also worth noting is the internal protection mechanism to limit the excursion of the dc link of voltage-source converter to limit the voltage across the IGBTs. Although the dc link protection is a required internal protection feature, both SEL and DNV-GL protection protections studies showed that it was effective in resulting in bypass for low level faults where the over-current threshold trip did not come into play.

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