Deploying Smart Wires at the Tennessee Valley Authority (TVA)

August, 2014

Contents

Executive Summary

In October 2012, the Tennessee Valley Authority (TVA) took the first step along the path to the grid of the future and simultaneously became the first utility to think differently about how the transmission network is both operated and planned. In a series of firsts, this pilot project also became the maiden deployment of the Smart Wires innovative power flow control solution and represented one of the first ARPA-E technologies to advance to commercialization.

Since its founding, Smart Wires has been a leader in developing power flow control solutions for the transmission network. The technology, which is designed and manufactured in the United States, offers its customers a unique solution to improve the flexibility of their existing transmission networks and meet the challenges of the coming utility paradigm. These challenges include integrating vast quantities of renewable energy as required by state and Federal regulators and better managing the intermittent power flows that these sources introduce.

In 2009, TVA immediately recognized the game-changing potential of this technology and joined a consortium of utilities within NEETRAC (the Smart Wire Focus Initiative or SWFI group) to develop the first requirements of the Distributed Series Reactor, the predecessor to the PowerLine Guardian™ manufactured by Smart Wires today. Collaborating closely, Smart Wires and TVA successfully completed the installation of 100 PowerLine Guardian™ units in October of 2012, which was, as previously alluded, the first field deployment of this technology.

As of August 2014, the installation has continuously operated for 21 months and has been available 100% of the time to provide power flow control and sensing to support TVA system reliability. This report summarizes the findings from TVA's experience with Smart Wires' technology and provides technical information surrounding key performance indicators established for this test. It also highlights lessons learned and how these learnings have fed back into the development of future products.

TVA's cooperation was critical in putting together this report and Smart Wires would like to thank them for their ongoing support.

Summary of Key Findings

This report presents the results from the first deployment of Smart Wires technology on the network of the Tennessee Valley Authority (TVA). It describes the installation and operation of 100 PowerLine Guardian™ devices on a 161 kV line outside of Knoxville, TN. Specifically, the report covers the installation architecture, assessment of key performance indicators (KPIs) over the one-year test period, impacts on TVA's power system, and lessons learned. The major findings are summarized below.

Power flow control. The PowerLine Guardian™ system injected inductive impedance ranging from 0 to a nameplate capability of 0.6 ohms per phase. The pilot system demonstrated the ability to reduce power flow by over 2.5%, as intended by TVA. A full PowerLine Guardian™ deployment on this line could deliver up 7x the impedance (4.2 ohms per phase) and deliver greater power flow control to scale with future developments on the network. The units transitioned in and out of injection mode based on local current level set points and on average, the units were dispatched to inject 62% of the nameplate impedance.

System availability. Units responded to operator commands transmitted sensor data with a 99.7% availability. Over the course of the one-year test, 95% of the units were available for power flow control and real-time sensing. Two primary drivers contributed to the loss in availability: 1. two units suffering from acoustic vibration were remotely forced into strict monitoring-only mode to eliminate noise, and 2. the communications systems on three units were unreliable.

Lessons learned. The aforementioned issues relating to availability have been addressed and eliminated from Smart Wires' current PowerLine Guardian™ offering. A combination of improved bolt design and increased torque reduced any acoustic noise generated by units in operation. Increasing backhaul capability, improving intra-system communication components, and performing additional environmental testing have mitigated any concerns over communication robustness and reliability.

Introduction

The TVA installation was completed in October 2012 on a 7.5 mile segment of the 21 mile TVA Knox-Douglas 161 kV transmission line. Following installation, use case testing began to ensure that the installation was functioning in accordance with modeled expectations. Beginning in April 2013, the installation was operated by TVA for a one-year test and performance was evaluated. The objective of the installation was to demonstrate the power flow control—reduce loading on the Knox-Douglas line and increase loading on two alternate semi-parallel lines—and real-time sensing capabilities of Smart Wires' technology. The lines are shown below in Figure 1. In addition, at least 95% of the units were required to be available for power flow control and data collection after one year of operation.

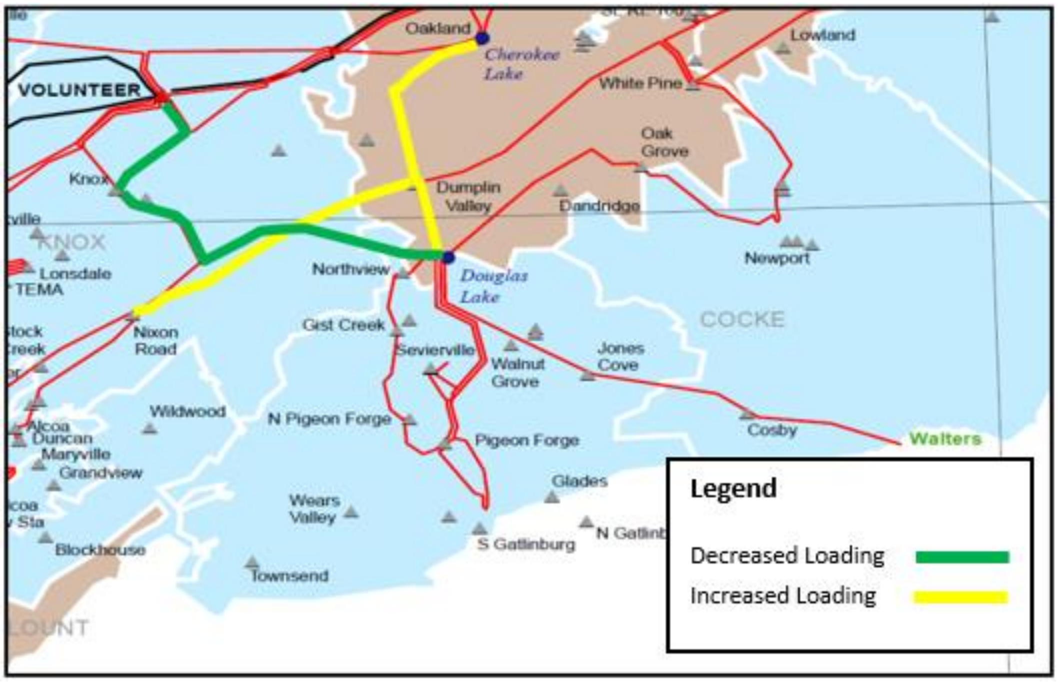

Figure 1: Map of the TVA Testbed and neighboring lines

Architecture of the TVA Installation

The Smart Wires solution is an end-to-end system to control power flows and measure the state of the transmission system. Figure 2 shows the communication layer of the end-to-end system. Components of the system include:

PowerLine Guardian™ – Changes line impedance by an incremental amount and measures the state of the transmission asset. Typically deployed en masse and distributed along the transmission line.

Cellular Enabled PowerLine Guardian™ – Serves as a PowerLine Guardian™ and communication bridge between the PowerLine Guardian™ fleet and the PowerLine Commander™.

PowerLine Commander™ – Performs a suite of services, which include Energy Management System (EMS) interface, data aggregation, archival, operator logging, and alert generation.

Each PowerLine Guardian™ is able to operate in one of four modes – standby mode, monitoring mode, injection mode, and *in extremis*. In standby mode, the unit is unable to change modes or communicate as the line current is insufficient to power the units. In monitoring mode, the secondary of the unit is shorted and negligible impedance is injected into the line. In injection mode, the magnetizing impedance of the PowerLine Guardian™ internal transformer is injected into the line. During *in extremis,* the unit protects itself from conditions that are outside of the set of allowable operating conditions (i.e. fault-inducted current).

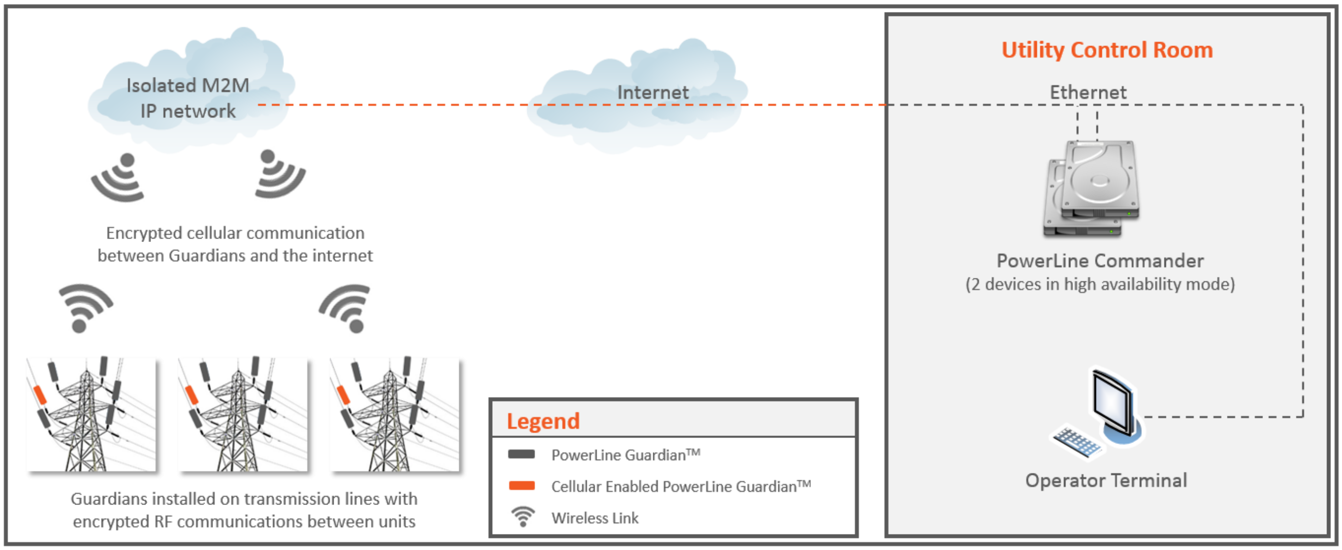

Figure 2: Overview of the Smart Wires communication layer

For the TVA installation, TVA accesses the PowerLine Commander™ through a web-interface. The PowerLine Commander™ graphical user interface (GUI) is shown in Figure 3 on the following page, with each green dot representing a unit in monitoring mode and each red dot indicating a unit in injection mode. The operator may put all units in monitoring mode via the *All Stop* button or put all units into injection mode using the *Max Inject* button. Alternatively, the operator may apply one of the pre-defined set point configurations, allowing units to self-determine the mode based on local conditions such as conductor temperature or current. PowerLine Commander™ may also be used to monitor the state of the entire installation or individual assets.

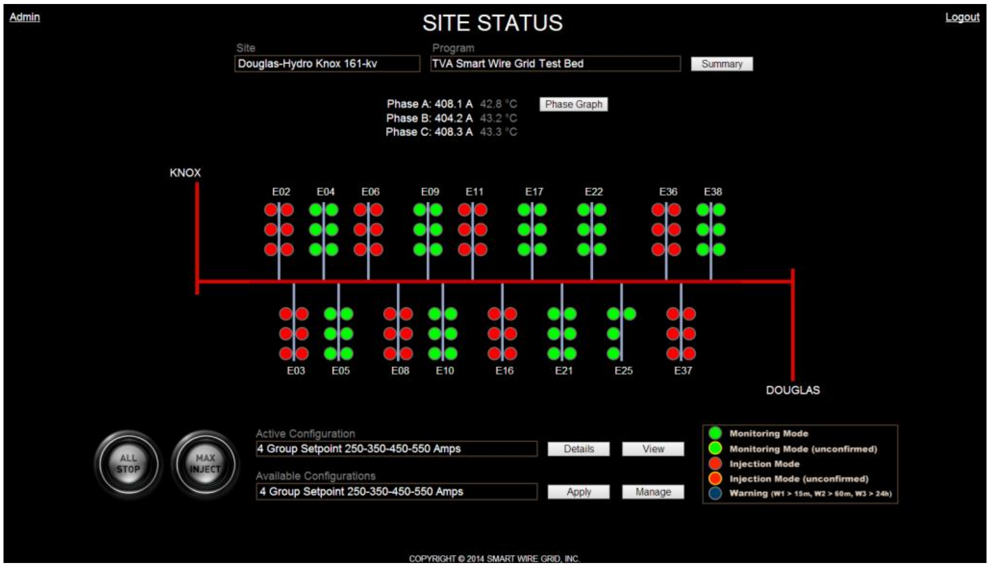

Figure 3: PowerLine Commander™ GUI

Performance Summary: One-year test

The installation was operated from 4/1/2013 through 3/31/2014 in Standby, Set Point, Max Inject and All Stop configurations. From April through December, the installation was operated exclusively in Set Point mode. From January through March, the installation was operated in all three configurations. In Set Point configuration, units were divided into the following four groups, each with a different current set points:

250 A on, 200 A off

350 A on, 300 A off

450 A on, 400 A off

550 A on, 500 A off

For example, if a unit was assigned to the 250 A on, 200 A off group, it would enter injection mode if the unit measured an RMS current at or above 250 A. If the RMS current dropped below 200 A, it would enter monitoring mode. When appropriately configured, the groups of set points allow the total injected impedance to follow the diurnal current profile as shown in Figure 4.

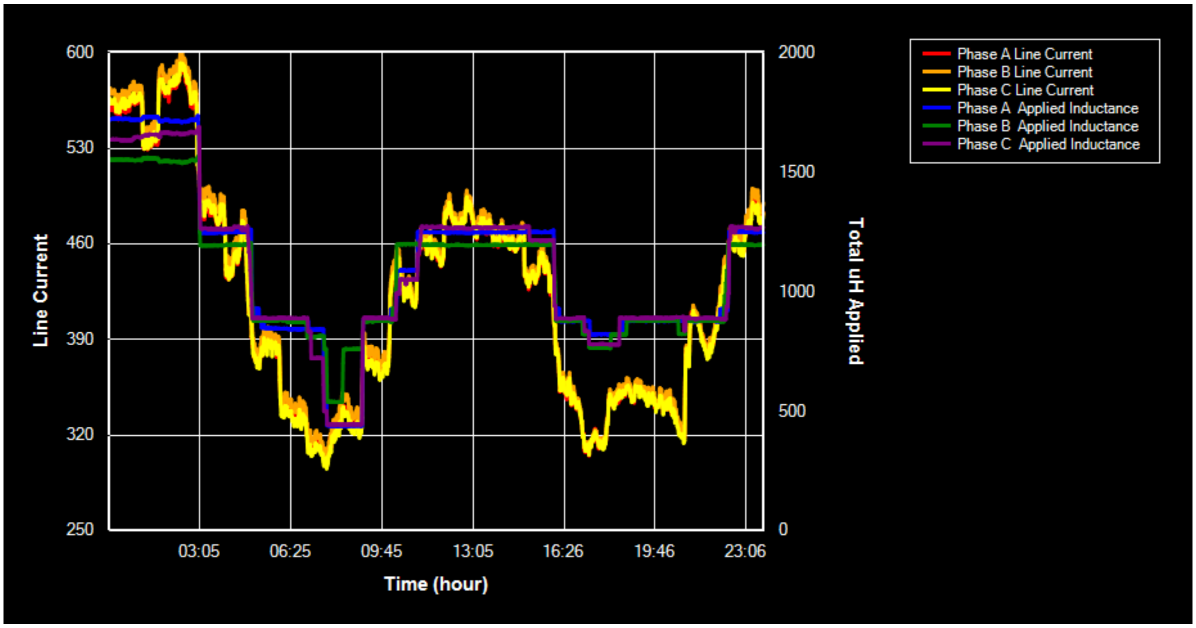

Figure 4: Sample day of Installation Activity during the One Year Test

Upon completion of the year of operation, summary statistics were generated to characterize uptime, usage type, and robustness of the communications system.

PowerLine Guardian™ Uptime and Mode of Operation

1. Period of record:

1.1. 4/1/2013 through 3/31/2014

2. Participating units:

- 98 of 100 PowerLine Guardians™ available at beginning of the one-year test
- 95 of 100 PowerLine Guardians™ available at end of the one-year test (95%). Units 9MB, 17BH, 17TH, 21TH, 38BH categorized as unavailable

3. Results:

3.1. Availability of participating units to change modes via remote command and/or send data (periods for which the conductor current was below the unit's minimum current level have been excluded from the set of potential available periods):

- Installation average: 99.728%
- Min for any given unit: 93.830%

- Max for any given unit: 100.00%

3.2. Availability of participating units to change modes via local command (periods for which the conductor current was below the unit's minimum current level have been excluded from the set of potential available periods):

- 100%

3.3. Number of times a unit entered injection mode:

- Installation total: 17244
- Min for any given unit: 0
- Max for any given unit: 404

3.4. Number of hours the units were in injection mode:

- Installation total: 330876 unit-hours
- Min for any given unit: 0 unit-hours
- Max for any given unit: 6379 unit-hours

3.5. Number of hours the units were in monitoring mode:

- Installation total: 542740 unit-hours
- Min for any given unit: 2381 unit-hours
- Max for any given unit: 8632 unit-hours.

Communications Robustness

Regular status polling was executed by the local Cellular Enabled PowerLine Guardian™ to determine the status of a particular unit. The robustness of PowerLine Guardian™ to Cellular Enabled PowerLine Guardian™ communications can be determined by comparing the frequency of polling errors to polling attempts. This calculation does not assess the robustness of backhaul communications between the PowerLine Guardian™ and the Operation Center.

1. Results:

1.1. Attempted communications events: 6.21×10^7

1.2. Unit polling errors: 4.49×10^5

1.3. Percentage packet loss: < 0.723 %

2. Conclusions:

One packet was lost for every 140 status inquires generated by the Cellular Enabled PowerLine Guardian™. After considering the outbound and inbound messages required for an exchange, one packet was lost out of 280 packets. As expected, some errors resulted during normal maintenance activities such as firmware updates.

Installation Impact on the Power System

A statistical test was performed to:

- determine if the installation impacts the power system
- quantify the magnitude of the impact

Data for the statistical test were extracted from all available Max Inject and All Stop events. During a Max Inject event, injected inductance of each phase was changed from zero to maximum over the course of a few minutes. During an All Stop event, the inverse occurred. For each Max Inject event, the phase current measurements were sampled at the last time step the installation inductance was zero and the first time step the inductance reached its maximum value. For each All Stop event, the phase current measurements were derived at the last time step the installation inductance was at maximum and the first time step the inductance reached zero.

Two samples were populated. The first sample (no injection) contains all measurements before transmission of the Max Inject command and all measurements after the All Stop had been confirmed. The second sample (max injection) contains all measurements after the Max Inject command had been confirmed and all measurements before transmission of the All Stop command. The no injection sample has a mean current 2.5% higher than the max inject sample. The null hypothesis that the two means are statistically equal was tested at a significance level of 0.05 using a one-side paired t-test. The result of the t-test supports rejection of the null hypothesis, suggesting that the mean current of the first sample is statistically higher than the mean current of the second sample. Thus, the statistical test supports the conclusion that current is lower in Max Inject than All Stop.

In conclusion, the statistical test demonstrates a high certainty that the installation had the expected effect on power flows. On average, switching the state of all units simultaneously changed the current flow by 10.4 A per phase. This corresponds to a change in flow of 3 MVA or approximately 30 kVA per unit. The installation would be more effective if additional units are added or the installation is moved to a line with lower natural inductance.

Lessons Learned

Overall, communication reliability was extremely high, but there were instances of limited failures. These issues have since been addressed with several product improvements. TVA's pilot deployment had only select units with full backhaul communication capability (Cellular Enabled PowerLine Guardian™) and all other units relayed messages through the backhaul enabled units. However, it was found that there was insufficient range of some intra-system communication leading to three units' inability to fully communicate back to the control center. This has been addressed by enabling every unit to act as a Cellular Enabled PowerLine Guardian™ with backhaul communication capability.

Excessive acoustic vibrations forced two units to operate exclusively in monitoring mode and prevented them from performing injection. The issue stemmed from the insufficient torqueing of bolts connecting the top half of the unit to the bottom half. After several thermal cycles of expansions and contractions the units clamping strength became inadequate. This problem has been solved with two design improvements. New units utilize more robust bolts and the main flange joint has been modified to improve clamping performance. The new design results in increased main bolt torque values and has been tested extensively for thermal and corrosion performance.

Conclusion

The TVA installation demonstrated the intended capabilities, meeting or exceeding all expectations, namely power flow control and real-time sensing. The installation met the requirement that 95% of units be available for operation and data collection after one year of operation and exceeded all requirements for communication uptime. On average over the one-year test, the installation was operated at 62% of nameplate impedance in injection mode. PowerLine Guardian™ to Cellular Enabled PowerLine Guardian™ communications were successful over 99.2% of the time. Across the set of instances where the entire installation was switched from monitoring to injection mode or vice versa, the average impact on power flow was 10.4 A per phase or 3 MVA. As of August 2014, the installation has been in continuous operation for 21 months.