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Report:	Research Performance Progress Report - Final	
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Award Number:	DE-EE0007195	
Prime Recipient:	SenSanna Incorporated	
Prime Recipient Type:	For-Profit Company	
Project Title:	Low-cost wireless voltage & current grid monitoring	
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Date of Report:	12/31/2016	
Reporting Period (covered by this report):	10/01/2015 to 12/31/2016	

Contents

SenSanna Incorporated
Low-cost Wireless Voltage and Current Grid Monitoring

I. Executive Summary

This effort developed and demonstrated a laboratory prototype low-cost sensor system for wireless measurement of voltage and current on medium voltage (MV) power distribution lines. The PowerFree^{TM} LineSenS^{TM} system developed was demonstrated at the National Renewable Energy Laboratory's medium voltage outdoor test area in November, 2016. Voltage accuracy established during these tests based on reference measurements from LEM SCADA sensors and Lindsey Model 9650/C650G line sensor units met the project accuracy goal metrics of ± 2% for 60 Hz line voltages up to 13.8 kV_{rms} and ± 2.5A for currents ≤ 120A_{rms}.

Low-cost surface acoustic wave (SAW) wireless voltage and current sensor modules were produced using robust, long lived external sensors that utilize capacitive and inductive coupling to the MV lines. Rugged SAW wireless interface devices enable real-time wireless voltage and current measurements of grid elements without batteries and without harvesting power from the power line. The line monitoring units are remotely powered by radio frequency (RF) signals from a pole-mounted radio, meaning that data on grid conditions is available even during outage conditions. The ability to measure current and voltage, even with no current on the line, can enhance worker safety by detecting unexpected voltage and current that may be present on power lines that are nominally isolated – for instance by verified 'open' reclosers.

There is currently an industry-wide initiative to enhance grid operating efficiency and stability through the increased use of dynamic controls and automation. For proper operation of these systems, near real-time feedback on grid condition is necessary. Low-cost distributed line monitors will provide detailed location-based insight into the operation of the power distribution grid, providing information on grid condition with a granularity that is currently unavailable. This information will enable operators to analyze and understand the grid stresses introduced locally by photovoltaic (PV) fluctuations and will allow utilities to develop local energy storage and control strategies that are prerequisite to reducing the cost of interconnection studies and exceeding the current 'hard caps' on solar, steps that will be essential to eliminating this barrier to ubiquitous solar.

II. Accomplishment & Milestone Update

The overall objective of this Tier 0 effort was to develop and demonstrate operation of an innovative functional laboratory prototype wireless voltage and current sensor system for monitoring of distribution grid power lines utilizing rugged low-cost SAW wireless interface devices. This was accomplished, as evidenced by the successful demonstration tests of the prototype system conducted at the National Renewable Energy Laboratory (NREL) in Golden Colorado in November 2016.

The laboratory prototype wireless sensor system developed consists of three line-mounted units (one for each phase) and a remotely mounted transceiver radio. The radio, which will be much smaller and pole mounted in future versions, in this Tier 0 effort was a rack-mount size software defined radio based on commercially available component evaluation boards and modules, controlled by a PC-based LabView user interface. In Tier 1, this radio will be integrated to produce a significantly smaller radio (about the size of a hand-held digital voltmeter) that is ruggedized for extended operation in a pole-mounted environment. Optimized antennas will also be developed, and the RF link quality will be improved.

The line-mounted units developed in Tier 0 (see Figure 1) consist of two hot line clamps (one that secures the unit to the power line and the other that closes the line unit around the line), an electric field probe and SAW device PCB module (both housed in the 6” diameter cylinder on the right in this photo), and a current transducer (CT) – left in photo – for line current measurement. As can be seen from Figure 1, in the Tier 0 prototype, CT and electric field probe housings were plastic. Poly-lactic acid (PLA), a 3-D printable plastic was used for rapid prototyping of these cases, which were secured using cable ties during testing. In Figure 1 the antenna is not connected, but the gold SMA connector for the antenna can be seen protruding from the SAW/PCB module housing.

Figure 1. *Tier 0 line-mounted wireless sensor prototype.*

The Tier 0 prototype, wrapped in plastic, withstood weather ranging from 77°F and sunny to 19°F with driving snow during demonstration testing Nov. 14 – 21, 2016 in the medium voltage outdoor test area (MVOTA) at NREL. Figure 2 shows the three line units of SenSanna's PowerFree^{TM} LineSenS^{TM} system mounted on the three phases of overhead power lines in the MVOTA. The second line in the power system is the neutral line. Sensor system antennas are positioned horizontal to the power lines. While plastic was sufficient to protect the system when exposed to variable weather (sun, rain, and snow) during this one-week long set of tests, this system is clearly a laboratory prototype that has not been ruggedized to withstand long-term exposure to the elements in the MV line environment. In Tier 1, we propose to modify the Tier 0 line units to produce smaller, lighter weight, fully encased and weatherproof prototype line units suitable for extended field trial testing (weeks to months). The units will target 15 kV-class OH distribution lines, which are used by over 90% of utilities. Consideration will be given in the line unit design to provide modularity that will allow the casing and line mounting structure to also be used for 5 kV, 25 kV, and 35 kV-class lines.

Figure 2. *Tier 0 laboratory prototypes being tested at the medium voltage outdoor test area (MVOTA) at NREL in Golden CO. The weather during our tests was quite variable, changing from sunny and warm to heavy snow in 24 hours.*

Extensive testing of the prototype wireless line monitoring system was conducted to establish system operating capabilities, both in a MV laboratory test setup and at NREL. A variety of tests were conducted, the majority of which were some combination of two basic types – ramp tests and on/off tests. In ramp tests, the line parameter (voltage and/or current) starts at zero (or another starting value), then ramps linearly to a target value over a defined time period (10 seconds nominal), holds at the target value for a defined time period (2 seconds nominal), ramps back to the starting value over a defined time period (10 seconds nominal), and then turns off. Other variations of the ramp test were used, with different ramp rates and times, and the time per ramp test was typically 30 seconds or less. For on/off tests, the test starts with the line off (no voltage or current), and after a few seconds we switch on voltage (or current) and hold that line condition for a defined time period (10 seconds nominal), and then switch the line off. The typical time per on/off test was approximately 25 seconds.

These and other test types were used to investigate system operation at various frequencies, power factors, and voltage and current combinations. Freeform current and voltage ramping tests (controlled manually rather than by the signal generator) were also performed to obtain some interesting videos of the system responses. System limitations restricted NREL testing to voltages of up to ~14kV (line-to-line, rms) and currents of up to $30A_{rms}$, with line operating frequencies from 58 Hz to 62 Hz. The MV laboratory test setup permitted separate control of both current and voltage, enabling system characterization over a wider range of line conditions. Tests performed in the lab included line currents up to 600 A_{rms} and (separately) voltages of up to ~20 kV_{rms} line-to-ground (34.6 kV_{rms} line-to-line), with selected tests performed at operating line frequencies of 45 Hz to 75 Hz. Thus, while the NREL demonstration testing was performed on 15 kV-class power lines, the prototype units were tested in the lab with conditions typical of 25 kV and even 35 kV-class lines.

System tests demonstrated the prototype wireless sensor-tag system operating, with the transceiver radio collecting data at a rate of 1 kHz from the 3 individually identifiable line units mounted on the power line(s). Extraction of the current and voltage waveforms provided information on relative phase (current leading or lagging voltage) for power factor (PF) tests using inductive and capacitive loads. Due to space restrictions, only a small set of the test results will be included in this final report, along with a summary of significant findings.

Test Results:

Voltage ramp testing was conducted in the laboratory to establish system transfer functions for voltage, enabling extraction of measured voltage as shown below in Figure 3. Good agreement is seen between measured voltage and applied line voltage throughout these tests. Due to the nature of the lab test setup, there is an ambiguity in the scaling factor for electric field intensity between the lab test setup used and a real overhead power line. Hence additional tests were conducted on an overhead line at NREL to verify and refine system voltage transfer functions.

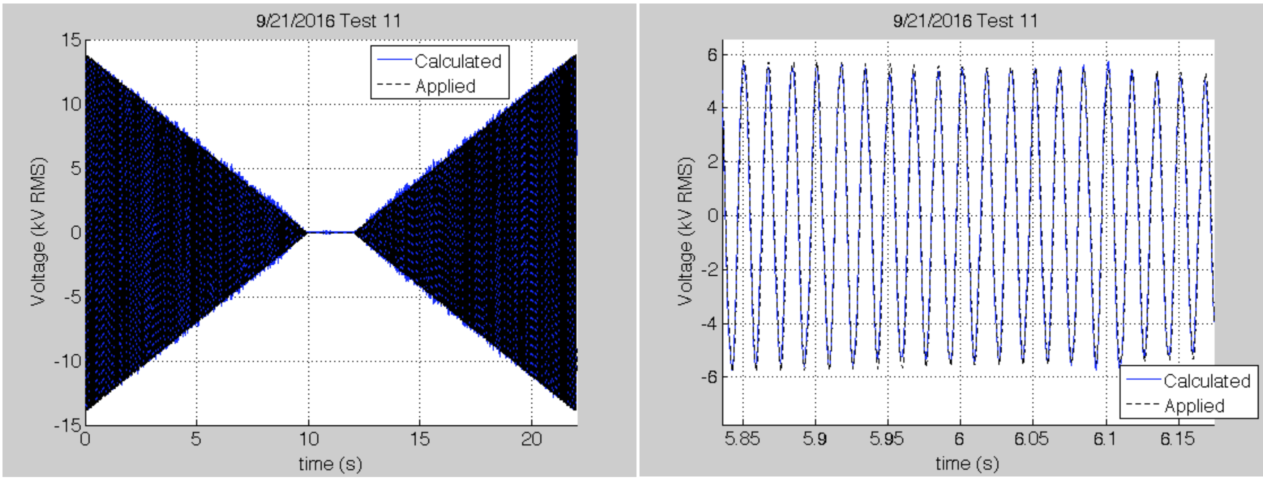


Figure 3. *Voltage ramp testing in MV laboratory test setup – applied vs. measured voltage for an entire single test (left) and expanded view (right).*

Lab testing for current accuracy produced the mean absolute error levels shown in Table 1 for each system at various current levels, satisfying the established Tier 0 target accuracy metric of ± 2.5A for currents ≤120A_{rms}. Lab testing for voltage accuracy produced the results shown in Table 2 for various voltage ranges for each system, satisfying the target accuracy metric of ± 2% for voltages above 1kVrms, which constitutes the operating condition for a majority of utility lines, although two of the systems fail to meet the target of ± 30V for voltages ≤ 1kV_{rms}.

Table 1. *Mean absolute error for current readings for each system.*

	0 – 5 A_{rms}	5 A_{rms} – 10 A_{rms}	> 10 A_{rms}
System 1	0.299 A	0.279 A	1.20 A
System 2	0.298 A	0.279 A	1.21 A
System 3	0.288 A	0.132 A	1.66 A

Table 2. *Mean absolute error for voltage readings for each system.*

	0 - 14 kV_{rms}	<1 kV_{rms}	1 kV_{rms} – 14 kV_{rms}
System 1	2.1%	41.7 V	1.95%
System 2	1.6%	29.4 V	1.49%
System 3	2.0%	48.3 V	1.76%

While ordinary power lines in the U.S. operate at 60Hz, seldom varying more than ± 2Hz, we chose to test our sensors at power line signal frequencies ranging from 45Hz to 75Hz. This testing confirmed that our responses are slightly frequency dependent, but we can extract the frequency of the fundamental line voltage very accurately and compensate for this frequency dependence. Figure 4 plots line frequency as measured by the wireless system vs. applied line frequency, and we observe nearly perfect linearity and very good test repeatability as seen by close clustering of data – each point corresponds to three tests. Figure 5 shows the error in the individual frequency measurements, which is < 0.1 Hz for all tests.

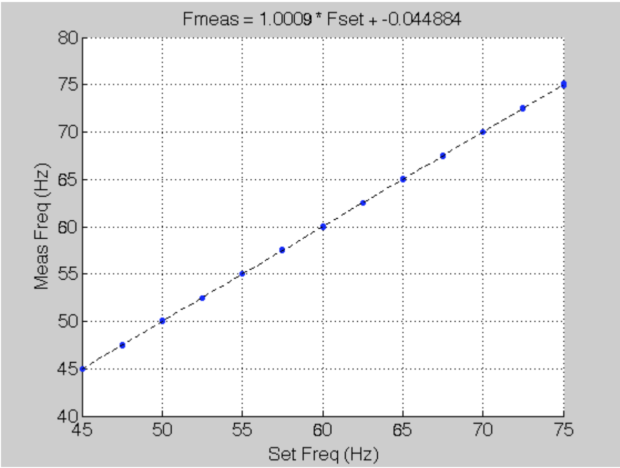


Figure 4. *Line frequency as measured by our wireless sensor system vs. applied frequency.*

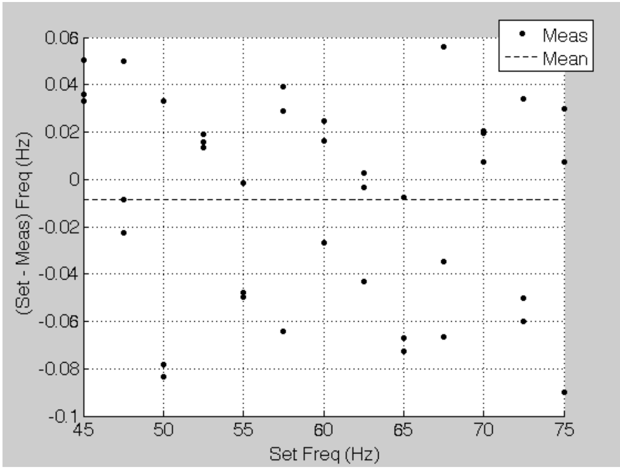


Figure 5. *Error in frequency extracted from individual line tests.*

Demonstration testing was done at NREL with the line units mounted on the three phases of a 15 kV-class 3-phase power distribution system. Voltage and current accuracy were established during these tests through comparison to reference measurements from NREL's SCADA and line mounted measurement systems. The SCADA system used LEM AV-100-750 sensors (accuracy ± 0.7%) for voltage measurement and LEM LF 2005-S sensors (accuracy ± 0.3%) for current. Lindsey Model 9650/C650G sensor units (voltage & current accuracy specified as ± 1%) were installed on the cross bar at one end of each phase of the MVOTA power line system, including all three phases and the neutral (see Figure 2). Interestingly, these two reference measurement systems did not always agree, with differences in voltage measurements ranging from -5.5% to +13.5% for Lindsey units relative to SCADA, and Lindsey current measurements differing from SCADA by up to ~4A with errors increasing with applied current (see Figures 6 and 7). Since the accuracy of our sensor system is measured relative to these reference systems this disagreement in reference measurements will need to be resolved before we can finalize our system accuracy. But since only these reference systems were available, we used them to generate calibration curves for our system, and assess system accuracy relative to SCADA current and Lindsey voltage measurements.

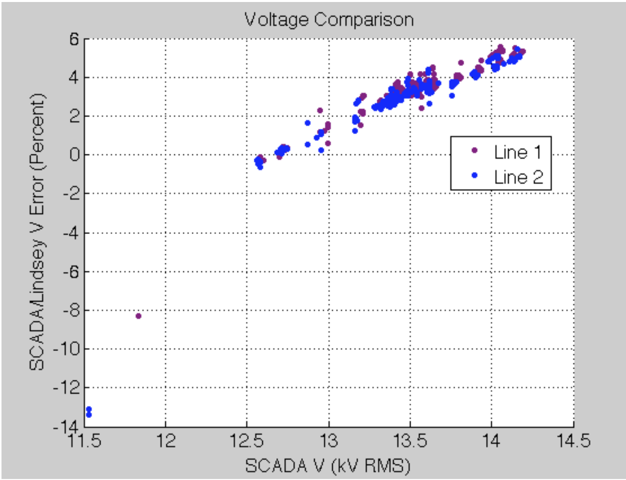


Figure 6. *Error in Lindsey voltage readings relative to SCADA measurements.*

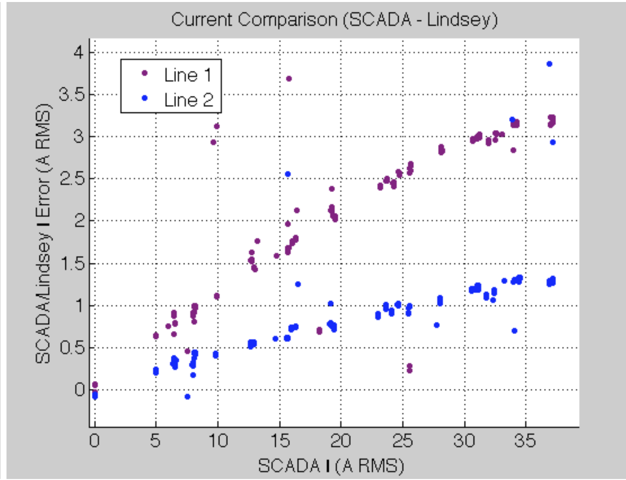


Figure 7. *Error in Lindsey current readings relative to SCADA measurements.*

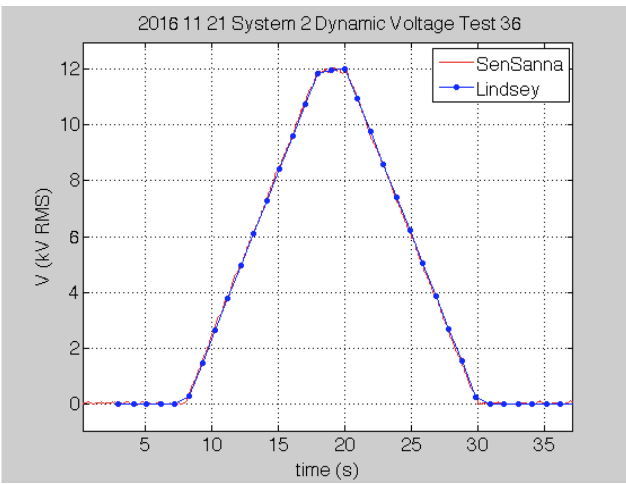


Figure 8. *Voltage calibration for system 2.*

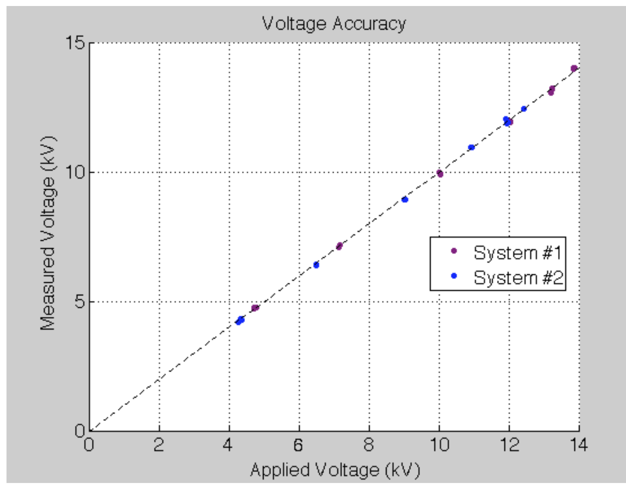


Figure 9. *Measured vs. applied voltage system 2.*

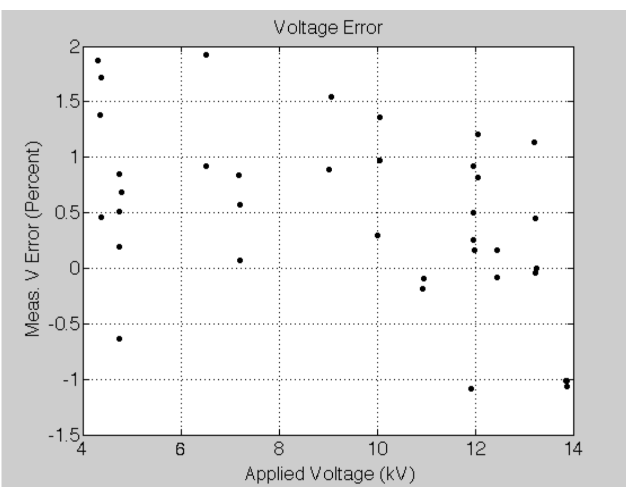


Figure 10. *Voltage accuracy for NREL tests.*

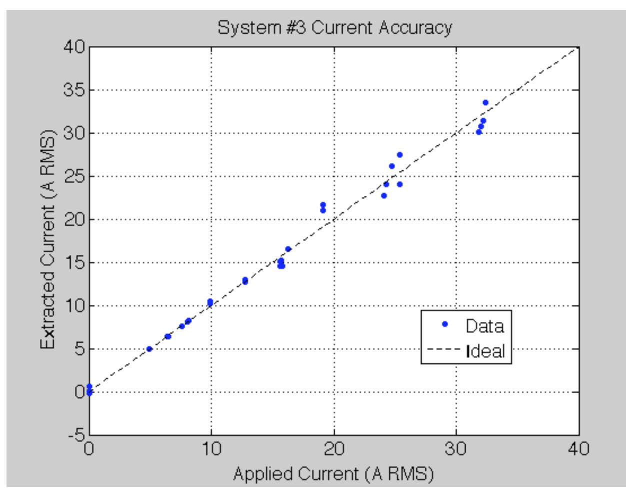


Figure 11. *Measured vs. applied current.*

Figure 8 shows the Lindsey voltage data used for calibration of line unit system 2. The Lindsey data points – taken at 1 second intervals – are shown in blue, while the measurements produced at a 1 kHz rate by SenSanna's wireless line monitor appears to be continuous in time, as shown in red in Figure 8. As expected, the agreement between calibration data and the measurements that generated it is quite good. A better measure of the accuracy of voltage measurements made by our system is provided by comparing the voltages extracted from all of the voltage measurements taken with the 'actual' applied voltage, as determined by Lindsey sensor measurements. Figure 9 plots measured voltage vs. applied voltage, and a very linear relationship is observed. We note that there is such close clustering of data points in Figure 9 that the number of tests this plot represents cannot be determined well. Figure 10 is a better way of assessing this, plotting the error in the measured voltage (in percent) relative to the applied voltage. Here we see that the ~ dozen points on Figure 9 actually depict 36 individual tests, with tests at the same voltage producing very closely clustered measurements. This shows good reproducibility of measurements using the prototype line sensors. Also, Figure 10 shows that SenSanna's system meets the ± 2% (or better) goal for line voltages up to 13.8 kV for 60Hz measurements. More detail on the accuracy and precision of voltage measurements made by SenSanna's wireless sensor system, relative to readings from the NREL Lindsey sensors is provided in Table 3. For 60 Hz line signals, the prototype measurements were within ± 1.14% of the measurements from the Lindsey reference sensors. For 58 Hz and 62 Hz line voltages, the slight frequency dependence observed for the prototype system leads to somewhat of a degradation in accuracy. This frequency dependence can be incorporated into future system transfer functions to improve accuracy for non-60 Hz signals.

Table 3. *Voltage measurement accuracy for NREL tests.*

Figure	Frequency	Voltage Reading & Accuracy (kV_{rms})			Precision (1s)
		Lindsey	SenSanna	Difference	
28	60 Hz	4.72	4.75	0.03 (0.63%)	± 0.05
29	60 Hz	7.16	7.10	-0.06 (-0.84%)	± 0.05
30	60 Hz	10.0	9.97	-0.03 (-0.30%)	± 0.04
31	60 Hz	11.99	11.97	-0.02 (-0.17%)	± 0.05
32	60 Hz	13.20	13.05	-0.15 (-1.14%)	± 0.03
33	58 Hz	4.82	4.7	-0.12 (-2.49%)	± 0.05
34	62 Hz	4.74	4.50	-0.24 (-5.06%)	± 0.13

Figure 11 shows measured current from the line sensors vs. applied current as determined by SCADA measurements. The current measurement accuracy met the established goal of better than ± 2.5A (for currents ≤ 120A_{rms}), although tests were only conducted up to 30A. Table 4 provides more detail on the accuracy of current measurements made by the prototype wireless sensor system during NREL tests at various current levels.

Note that while the prototype system met target accuracy metrics for this program, the accuracy of current measurements is better at very low currents. This is the case because as current levels increase, the SAW sensor response amplitude decreases, reducing signal to noise ratio (S/N) and making any noise detected by the radio more apparent relative to the signal. This effect can be mitigated in future systems by:

- Modifying the CT output voltage to restrict the system operating point to a less nonlinear portion of the system transfer function;
- Improving the radio (reducing the receiver noise figure, increasing the spectral efficiency of the transmitted sensor interrogation signal); and
- Improving the radio RF link (better antennas, reducing sensor insertion loss.

Table 4. *Current measurement accuracy for various current levels.*

	Current Measurement Error					
	0-10 A_{rms}		**0-20 A_{rms}**		**0-30 A_{rms}**	
	Mean(A)	**Max(A)**	**Mean(A)**	**Max(A)**	**Mean(A)**	**Max(A)**
System 1	0.06	0.17	0.38	2.5	0.60	2.8
System 2	0.25	0.71	0.57	2.4	0.80	3.3
System 3	0.14	0.53	0.34	2.5	0.53	2.5

The prototype wireless power line monitoring system has a LabView user interface (UI) for radio control and data acquisition and analysis. Figure 12 shows a snapshot of the final system user interface. We see the raw sensor data in the plot on the upper left, normalized amplitudes of each sensor response peak in the plot on the upper right, and measured voltage (lower left) and current (lower right) waveforms.

Power factor (PF) testing was conducted using the utility REDB configuration. In these tests, current was stepped up to six different levels, with applied loads suitable to produce power factors of 1, -0.8, and +0.8. Figure 13 shows the slight change in phase of our system responses with increased current level, which will require further evaluation. But for each current level, we see that for a PF of -0.8, current leads voltage by about 36°, while for PF of +0.8 current lags voltage by 36°. Figure 14 shows the extracted voltage and current waveforms for a small portion of three such tests, showing in-phase, leading, and lagging responses.

Tests of two line units at a time demonstrated that extracted voltage waveforms on the two lines are roughly the same amplitude, at a phase difference of 119.3°, very close to the 120° expected for a three-phase power system. These results are shown in Figure 15.

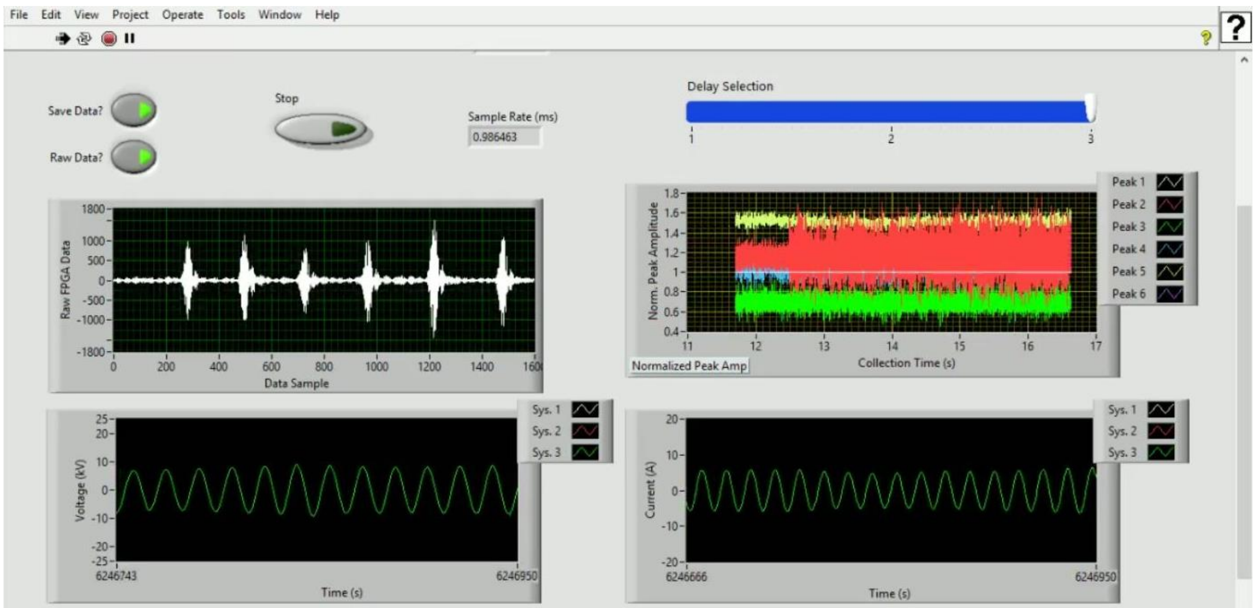


Figure 12. *Screenshot of the LabView user interface for prototype line monitoring system.*

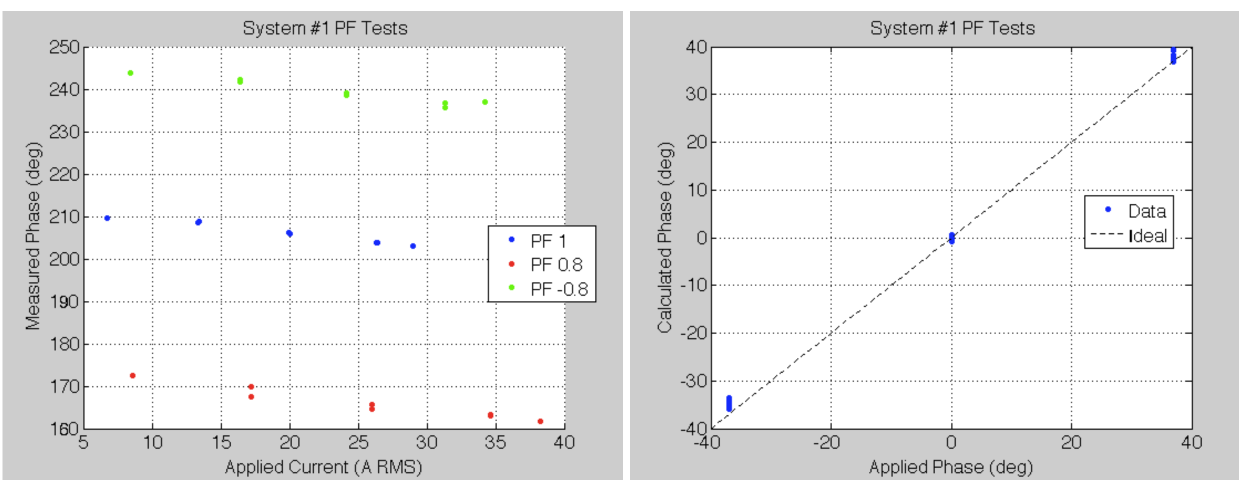
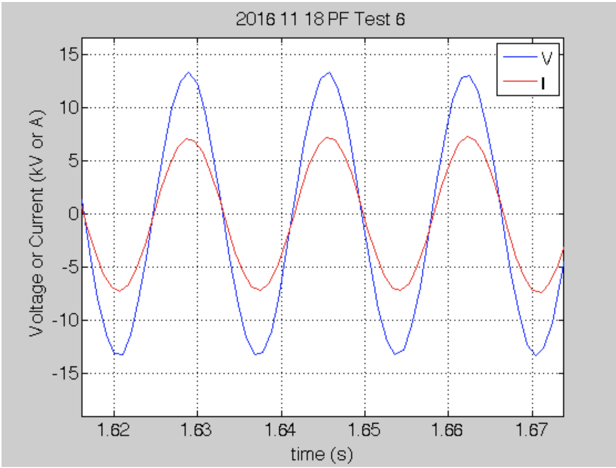
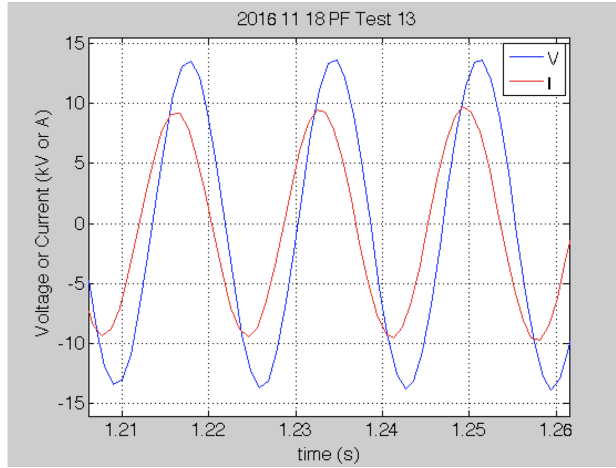


Figure 13. *Measured phase vs. current (left) and vs. applied phase (right) for system 1 PF tests.*





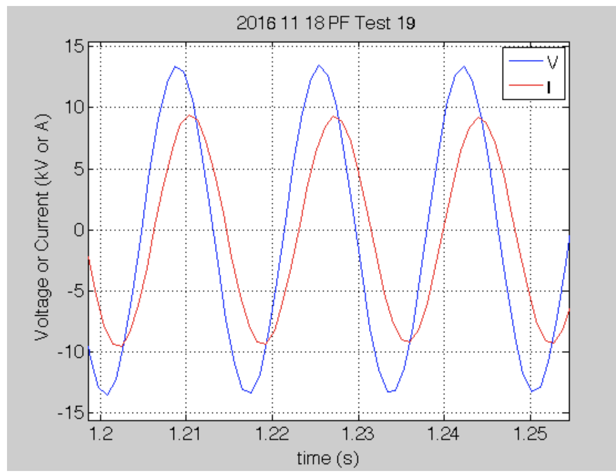


Figure 14. *Current and voltage waveforms for:*

(a) PF = 1 (above left) – voltage and current are in phase;

(b) PF = -0.8 (above right) – voltage leads current by 36°; and

(c) *PF = +0.8 (right) – voltage lags current by 36°.*

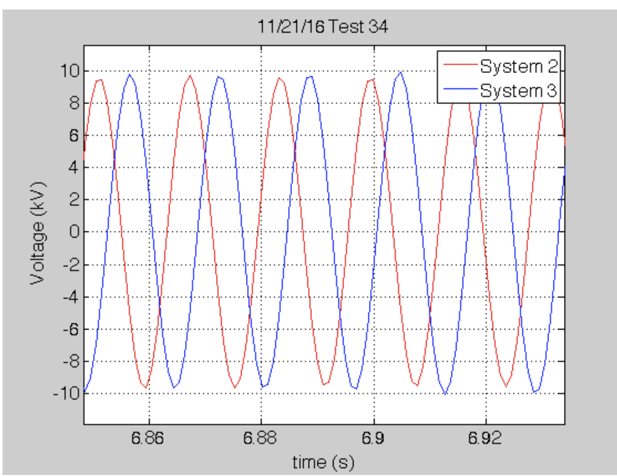


Figure 15. *Steady state voltage waveforms as read simultaneously from systems 2 and 3. The phase difference between the two line signals that was extracted from this data is 119.3 degrees, very close to the nominal phase difference between lines of a three phase power system (120 degrees).*

The plots shown herein reflect a very small subset of the data collected during hundreds of tests of the prototype wireless sensor system, both in the laboratory and at NREL. Additional data has been submitted to DOE in prior quarterly reports and deliverables.

Summary of Significant Findings:

This effort developed and demonstrated a laboratory prototype low-cost sensor system for wireless measurement of voltage and current on medium voltage (MV) power distribution lines. The PowerFree™ LineSenS™ system demonstrated at NREL in November 2016. Voltage accuracy for prototype system measurements met the project accuracy goal metrics of ± 2% for 60 Hz line voltages up to 13.8 kV and ± 2.5A for currents ≤ 120A, as confirmed by comparison to installed NREL reference SCADA and line monitoring sensor systems.

The prototype wireless power line monitoring system developed under this contract is entirely novel - unlike any other commercially available power line monitoring systems, the remotely powered PowerFree™ LineSenS™ system operates even in outage conditions (i.e. with no current on the line). In addition to enabling greater levels of solar installation on the grid, these systems will significantly enhance line worker safety. Since PowerFree™ LineSenS™ systems operate even with no current on the line, they are able to detect any current and voltage present on lines that are nominally isolated. For example, when reclosers have been opened and from the utility's perspective a line should be 'dead', voltage and current can still flow on the line from unanticipated sources. Such conditions can be detected real-time using the proposed system, reducing the risk of line worker injury or death.

Along with the technical accomplishments described above, SenSanna has initiated discussions with several electric utilities, most of which have expressed interest in the potential future availability of low-cost wireless line monitoring systems such as the one developed under this program. Several have indicated that the availability of sensors for monitoring power line conditions are a key part of their planned future efforts to automate and optimize grid operations, as well as confirming that such sensors will enable installation of greater levels of solar and other renewable distributed sources on the grid.

Discussions have included working with a utility for field testing of a production ready prototype to be developed in the next two years, and SenSanna's participation in utility technology development programs. One such proposed effort has the goal of turning each monitoring point into an 'intelligent' node, by incorporating into the radio information on expected normal power line operating conditions and how to interpret excursions from normal operation, allowing the radio to interpret measurements and provide actionable intelligence to the utility, rather than simply raw data on power line operating conditions.

III. Issues, Risks, and Mitigation

The only significant delay in project performance was caused by a scheduling delays related to unavailability of the NREL test facilities when SenSanna was ready to conduct demonstration tests. For future efforts, we will plan on scheduling such tests much earlier in the project, to anticipate long lead times for equipment availability. A no-cost extension through 12/31/2016 allowed us to complete demonstration testing and wrap-up the project.

IV. Proposed Changes in Approach

None.

V. Proposed Changes in Key Personnel

None.

VI. Project Output

This project produced a functional laboratory prototype wireless power line monitoring system "PowerFree™ LineSenS™" that is completely unique in the industry. Operating without batteries and without harvesting energy from the current in the power line, this system can operate and read current and voltage even in outage conditions where power lines carry little to no current. Other commercially available line monitoring systems either require batteries in the line mounted units, or harvest power from the line – which limits system operation to currents of about 6A or above. A second unique feature of the PowerFree™ LineSenS™ system is the low cost, which is made possible by the lack of radio electronics in the lie unit, and the extremely low cost of the core sensor technology.

A U.S. utility patent application (number 15/298,2725) entitled "Remotely powered line monitor" that discloses this novel technology was filed on October 20, 2016. SenSanna has elected to retain the IP rights, and intends to pursue international protection on this invention

VII. Follow-On Funding

SenSanna plans to apply for follow-on funding from the DOE SunShot program to continue product development of the technology demonstrated in this effort. We plan to request approximately $2 million in Tier 1 SunShot funding, to be partially matched by $500,000 in outside investment, to provide the capital required to transform the laboratory prototype developed in this effort into a commercially relevant production ready prototype that has been tested in relevant use cases. We anticipate submitting a proposal for this effort in February 2017, and hope that this will result in a funded program starting in mid-2017 and lasting for 24 months.

In addition to the above mentioned Tier 1 proposal, we plan to apply for a separate Tier 0 SunShot project that would adapt the wireless monitoring technology that was demonstrated in this effort to the monitoring of underground power distribution cables – an unmet market need identified by our commercial assessment under this project. Our planned proposal will request approximately $900,000 in DOE funds, for which we plan to provide matching funds of $225,000 from company operations and/or external investment.

SenSanna is currently pursuing a Series A capital round, with the goal of raising the funds required to provide cost sharing for the DOE programs mentioned above, and also additional capital needed for facility and staff expansions, investment in capital equipment, and other costs requisite for planned company growth. We plan to obtain commitments for the necessary funding within the first three calendar quarters of 2017.

VIII. Recipient and Principal Investigator Disclosures

No conditions that would require disclosure exist for either the recipient or the PI.

IX. Conflicts of Interest within Project Team

None.

X. Performance of Work in the United States

All work performed under this EERE Award was performed in the United States.

XI. Project Schedule Status

This project is now complete. For details on planned and actual completion dates for individual deliverables, see project schedule status table on the following three pages.

Project Schedule Status Table									
Deliverable	**Month Due** **% total EERE funding**	**Deliverable Title & Description: Specific, Measurable, Quantitative**	**Technical Tasks/Milestones related to completing deliverable**	**Planned Dates (Month)**		**Actual Dates (Month)**		**Status**	**% Complete**
				Start	**Complete**	**Start**	**Complete**	**Not Started, Ongoing, or Complete**	
D1	**2** **20%**	Technical 1. Based on survey results SenSanna will present suggested metrics to DOE and obtain DOE approval of: a. Elevated voltage range to be used for testing in D6 b. Voltage and current ranges to be used for field probe design in D2 2. Sensor diversity scheme established for 6 sensor tags that can operate together Business 1. Send survey on system requirements to at least 4 potential customers 2. Tabulate survey responses	Task 1: System and Component Simulation	M1	M10	M1	M11	C	100%
			Task 4: SAW Sensor-tag Prototyping & Baseline Testing	M1	M5	M1	M5	C	100%
			Task 8: Preliminary Commercial Feasibility Assessment	M1	M12	M1	M14	C	100%
D2	**5** **20%**	Technical 1. External field probes capable of reading voltage and current ranges agreed to in D1 designed, resolution estimated 2. Based on field probe resolution estimates and component performance projections SenSanna will present their suggested metrics on accuracy for HV testing in D6 to DOE and obtain DOE approval 3. SAW sensor-tags prototyped, baseline electrical performance testing complete 4. System simulation with measured sensor data showing all 6 working together Business 1. Summarize notional product requirements &	Task 1: System and Component Simulation	M1	M10	M1	M11	C	100%
			Task 2: External Component Selection, Design & Prototyping	M1	M8	M1	M10	C	100%
			Task 3: Antenna Prototyping	M1	M8	M2	M10	C	100%
			Task 4: SAW Sensor-tag Prototyping & Baseline Testing	M1	M5	M1	M5	C	100%
			Task 5: Sensor-tag Module Prototyping & Baseline Testing	M2	M8	M3	M11	C	100%

Project Schedule Status Table

Deliverable	Month Due % total EERE funding	Deliverable Title & Description: Specific, Measurable, Quantitative	Technical Tasks/Milestones related to completing deliverable	Planned Dates (Month)		Actual Dates (Month)		Status	% Complete
				Start	Complete	Start	Complete	Not Started, Ongoing, or Complete	
		features list based on survey results	Task 8: Preliminary Commercial Feasibility Assessment	M1	M12	M1	M14	C	100%
D3	**8** **15%**	Technical 1. Field probes prototyped & baseline tested, resolution calculated 2. Antennas prototyped and baseline tested 3. Sensor-tag modules baseline tested a. Wired data with varying DC voltage (w/o field probes) b. Wired data with DC voltage applied to field probes 4. LV and HV test plans completed , HV test plan reviewed by a national lab Business 1. Prepare technology capabilities/sensor system features pamphlet, request feedback from at least 4 potential customers 2. Obtain customer feedback from at least 2 customers	Task 1: System and Component Simulation	M1	M10	M1	M11	C	100%
			Task 2: External Component Selection, Design & Prototyping	M1	M8	M1	M10	C	100%
			Task 3: Antenna Prototyping	M1	M8	M2	M10	C	100%
			Task 5: Sensor-tag Module Prototyping & Baseline Testing	M2	M8	M3	M11	C	100%
			Task 7: Sensor System Integration & Lab Testing	M5	M12	M2	M14	C	100%
			Task 8: Preliminary Commercial Feasibility Assessment	M1	M12	M1	M14	C	100%
D4	**10**	Technical 1. Transceiver radio operable to read a set of 6 sensor-tags, and to extract [uncalibrated] a. Voltage from 3 sensor-tags b. Current from 3 sensor-tags, and c. The relative phase between current and voltage	Task 6: Transceiver Modification	M2	M12	M3	M12	C	100%
			Task 7: Sensor System Integration & Lab Testing	M5	M12	M2	M14	C	100%

Project Schedule Status Table

Deliverable	Month Due % total EERE funding	Deliverable Title & Description: Specific, Measurable, Quantitative	Technical Tasks/Milestones related to completing deliverable	Planned Dates (Month)		Actual Dates (Month)		Status	% Complete
				Start	Complete	Start	Complete	Not Started, Ongoing, or Complete	
	15%	(for each of 3 pairs of tags) 2. LV test fixture assembled Business 1. Preliminary commercial feasibility assessment complete per subtask 8.2	Task 8: Preliminary Commercial Feasibility Assessment	M1	M12	M1	M14	C	100%
D5	12 29%	Technical 1. Low voltage lab testing complete; SAW sensor-tags accurate to within tolerances agreed to in D2 2. Laboratory testing at elevated voltages completed at a National Lab; SAW sensor-tags accurate to within tolerances agreed to in D2 Business 1. A total of at least 2 letters of support obtained from potential customers	Task 6: Transceiver Modification	M2	M12	M3	M12	C	100%
			Task 7: Sensor System Integration & Lab Testing	M5	M12	M2	M14	C	100%
			Task 8: Preliminary Comm'l Feasibility Assessment	M1	M12	M1	M14	C	100%
D6	12 1%	Technical 1. Complete final award reporting requirements (technical and financial)	Task 8: Preliminary Commercial Feasibility Assessment	M1	M12	M1	M14	C	100%
			Task 9: Program Management	M1	M12	M1	M15	C	100%

XII. Budget Status

This project incurred a slight budget overrun of $32,733.09 or 5.085% as shown in the table below, which increased SenSanna's cost share from the budgeted 22.323% to 26.082%. The DOE total cost remains unchanged at $500,000.

	EERE Share	SenSanna Cost Share	Total
Approved Budget	$ 500,000.00	$ 143,695.00	$ 643,695.00
Actual incurred costs Q4 2016	$ 105,928.55	$ 14,090.02	$ 120,019.57
Cumulative costs to date	$ 500,000.00	$ 176,428.09	$ 676,428.09
Remaining balance	$ 0.00	$ -32,733.09	$ -32,733.09

Considering individual cost components, project expenditures were kept fairly close to budgeted amounts for each category as shown in the table below. Since no cost category incurred expenses that varied from the budgeted amounts by more than 10% of the total project budget, there was no need to reallocate funds between cost categories.

	Budget	Actual	Variance (actual – budget)	
			Dollars	% of Total Cost
Personnel	$ 225,546	$ 240,078.34	$ 14,532.34	2.26%
Fringe Benefits	$ 65,499	$ 69,718.74	$ 4,219.74	0.66%
Travel	$ 13,533	$ 11,019.01	$ -2,513.99	-0.39%
Supplies	$ 16,559	$ 23,331.35	$ 6,772.35	1.05%
Contractual	$ 54,040	$ 43,636.31	$ -10,403.69	-1.62%
Other	$ 24,336	$ 30,067.10	$ 5,731.10	0.89%
Indirect Charges	$ 244,182	$ 258,577.24	$ 14,395.24	2.24%
Total	**$ 643,695**	**$ 676,428.09**	**$ 32,733.09**	**5.09%**

XIII. Certification of Compliance

I have the authority to make the following certification on behalf of the Prime Recipient named above. On behalf of the Prime Recipient, I certify that the information provided in this Research Performance Progress Report is accurate and complete as of the date shown below. I understand that false statements or misrepresentations may result in civil and/or criminal penalties under 18 U.S.C. § 1001.	
SIGNATURE: Jacqueline H Hines	DATE: 12/31/2016
TYPED NAME: Jacqueline H. Hines	
TITLE: CEO and Principal Investigator	
PERFORMER/ORGANIZATION: SenSanna Incorporated	