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Smart Inverter Advanced Metering Infrastructure Integration Using Smart Energy Profile

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Technical Update, May 2013

EPRI Project Manager

G. Aumaugher

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The following organizations, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Electric Power Research Institute (EPRI)
3420 Hillview Ave
Palo Alto, CA 94304

Principal Investigator
G. Aumaugher

nebland software, LLC
859 Richborough Rd.
Green Bay, WI 54313

Principal Investigator
B. DuPont

Sacramento Municipal Utility District (SMUD)
6201 S Street
Sacramento, CA 95817

Principal Investigator
Obadiah Bartholomy

Principal Investigator
T. J. Vargas

Itron Inc.
2111 North Molter Road
Liberty Lake, WA 99019-9469

California Public Utilities Commission (CPUC)
505 Van Ness Avenue
San Francisco, CA 94102

California Solar Initiative (CSI) Research, Development, Demonstration, and Deployment (RD&D)
New Solar Homes Partnership
1516 Ninth Street, MS-45
Sacramento, CA 95814

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ABSTRACT

In order to enable cost effective integration of high penetrations of photovoltaic (PV) systems, some level of communications and direct control of the PV inverters is expected to be necessary. Approaches leveraging broadband and utility remote terminal units (RTU) are generally not scalable to smaller scale residential or small commercial inverters. Given the potential addition of many thousands of residential PV systems in the coming years, identifying a low-cost solution allowing control and communications with residential systems has some level of urgency. Cost constraints significantly limit the types of communications and controls strategies that may be employed, and suggest the need to leverage existing in-place and available communications infrastructure such as broadband connected routers delivering a wireless signal or utility advanced metering infrastructure (AMI) networks. In order to understand the capabilities, advantages, and limitations of using the AMI network to provide communication and control functions desired by the utility, demonstration of this approach is important.

Sacramento Municipal Utility District (SMUD), funded through a grant from the California Public Utilities Commission (CPUC) California Solar Initiative (CSI) Research, Development, Demonstration, and Deployment (RD&D) program, worked with EPRI to demonstrate this approach. EPRI provided technical expertise in this integration by developing technology to facilitate a demonstration in EPRI's lab as well as at SMUD's Smart Grid Home Area Network (HAN) Test lab which is used to evaluate compatibility with SMUD's production AMI network deployed by Silver Spring Networks.

As a proof of concept, this demonstration verified there are no technical issues to prevent the control of smart inverters using the demand response/load control (DRLC) and metering commands built into Smart Energy Profile (SEP) 1.1. This demonstration did not address the operational issues that would be encountered re-purposing these commands. One of the objectives of this research was to improve understanding of the capabilities, advantages, and limitations of using the in-place AMI network to accomplish communications and control functions with a widespread deployment of smart residential PV inverters.

Achieving broad deployments with residential inverters could be inherently low cost given the expected costs of the ZigBee chips themselves are expected to be on the order of a few dollars per unit. Interfaces that have been developed to support Demand Response functionality can be leveraged for communicating with inverters using the same protocols. The use of the mesh network offers some inherent reliability due to redundancy of the communications pathways afforded in a mesh.

This approach is not without its flaws, the most significant being security concerns and resulting testing requirements for devices that will be communicating directly with the AMI network.

Keywords

Smart Energy Profile (SEP)
Smart Inverter
ZigBee

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 OBJECTIVES

In order to enable cost effective integration of high penetrations of photovoltaic (PV) systems, some level of communications and direct control of the PV inverters is expected to be necessary. While approaches leveraging broadband and utility RTU's have been demonstrated for commercial and utility scale inverters, these solutions are generally not scalable to smaller scale residential or small commercial inverters. Given the potential addition of many tens, and even hundreds of thousands of residential PV systems in California in the coming years, identifying a low-cost solution allowing control and communications with residential systems has some level of urgency. Based on the SunShot targets for residential inverter prices of approximately $0.12 per kW by 2020, communications and control functionality will likely to need to be a small fraction of this, at perhaps $0.01 per kW, or $40 for a 4kW residential inverter. Such constraints significantly limit the types of communications and controls strategies that may be employed, and suggest the need to leverage existing in-place and available communications infrastructure such as broadband connected routers delivering a wireless signal or utility AMI networks, such as have been deployed amongst most large California utilities including SMUD and the Investor Owned Utilities (IOU's). In order to understand the capabilities, advantages, and limitations of using the AMI network to provide communication and control functions desired by the utility, demonstration of this approach is important.

Sacramento Municipal Utility District (SMUD), funded through a grant from the California Public Utilities Commission (CPUC) California Solar Initiative (CSI) RD&D program, worked with EPRI to demonstrate this approach. EPRI provided technical expertise in this integration by developing technology to facilitate a demonstration in EPRI's lab as well as at SMUD's Smart Grid Home Area Network (HAN) Test lab which is used to evaluate compatibility with SMUD's production AMI network deployed by Silver Spring Networks.

The primary benefits, if this approach is proven viable, to California's utility customers include a very low-cost method for communications and control of distributed PV which could substantially reduce the costs of PV integration, increase the amount of PV that could be added to the grid, and increase reliability of the grid under high PV penetration scenarios. Such an approach could also enable customers to benefit through a low cost means of offering grid services and improved response to utility grid pricing with distributed storage systems. Alternatives to finding such a low-cost approach may mean a more limited deployment of PV, higher costs invested in metering and interconnection study, as well as increased investment by utilities in mitigation solutions that do not leverage the capabilities inherent in the PV inverters themselves.

2 APPROACH

This demonstration was configured to use the typical communications architecture implemented by SMUD for demand response field implementations. The equipment and software used was existing infrastructure with the following exceptions:

1. The SMUD test facility did not have suitable solar panels or solar simulator available so a DC power supply was used as a substitute
2. EPRI developed a Smart Energy Profile (SEP) Gateway described later in this document to translate the SEP 1.x commands in the Fronius interface protocol.
3. Test certificates were used rather than production certificates since the EPRI SEP Gateway was a prototype unit

The idea behind this implementation of smart inverter control using SEP 1 is to use the existing message structure to support DER control and monitoring. Since SEP 1 did not have native commands to accomplish these functions, it was necessary to select substitute functions that could be repurposed. EPRI provided a SEP Gateway to accomplish the tasks of translating the SEP 1 DRLC and metering commands into messages that the Fronius smart inverter understands and implementing the messages in the Fronius interface protocol.

Test Architecture

Testing was conducted at two locations. Testing using utility equipment was conducted at the SMUD facility at 6201 S Street Sacramento, CA. The equipment arrangement for the testing at the SMUD facility is shown in Figure 2-1.

This demonstration test was conducted in SMUD’s Smart Grid HAN Compatibility Lab on April 23. A DC power supply was used to replace a PV source for the inverter in both test setups due to unavailability of a suitable PV source at the test facilities. Because the focus of this effort was on the capabilities and limitations of the AMI network for delivering control signals, this choice of power supply did not impact any of the research objectives. Previous tests have demonstrated the ability to curtail the output of a PV system using a control signal sent to the inverter.

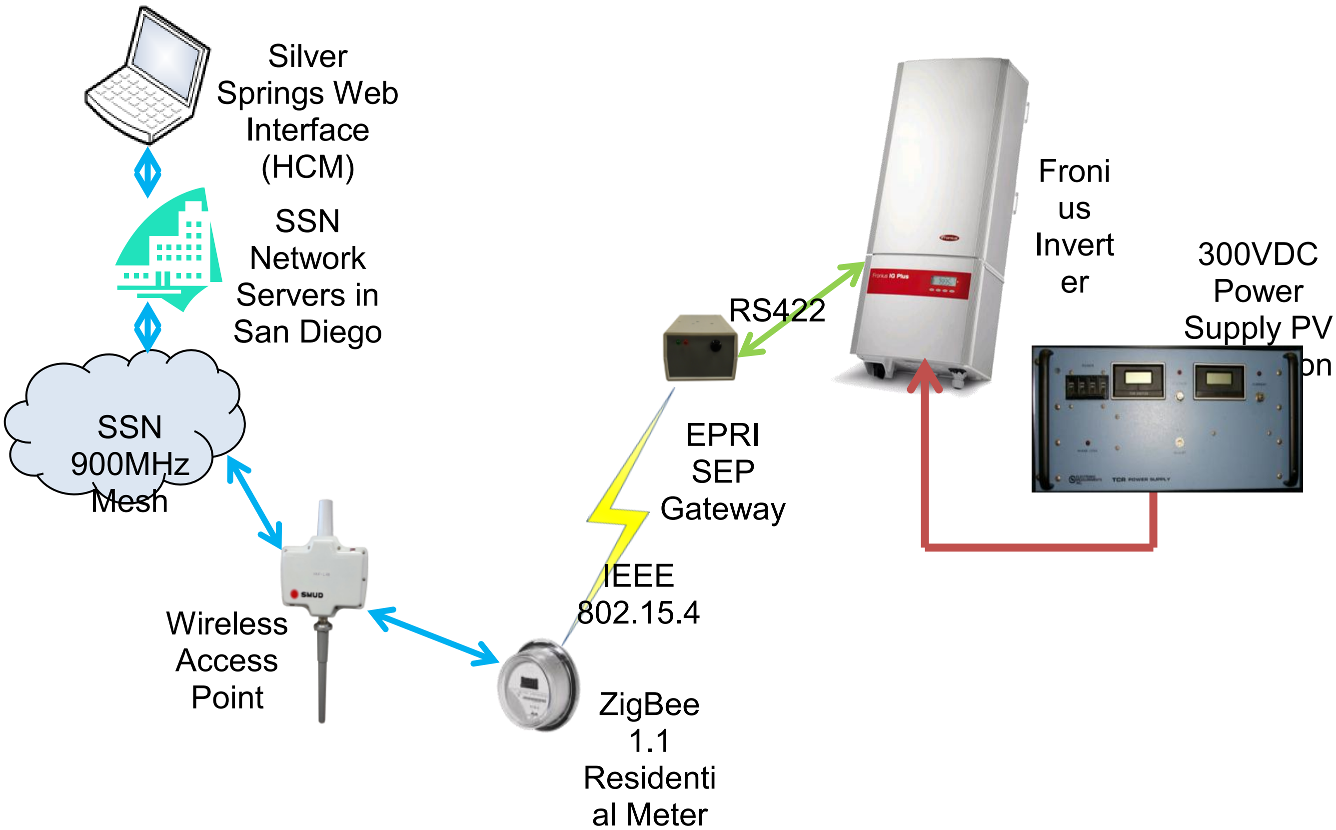

Figure 2-1
Testing at SMUD facility

EPRI developed an interface device that enables connectivity of the inverter to the Home Area Network (HAN) of a meter in an AMI system. Figure 2-2 depicts the test arrangement used during development by EPRI. Silver Spring Networks (SSN) provided a Field Service Unit (FSU) to act as their interface to the EPRI SEP gateway.

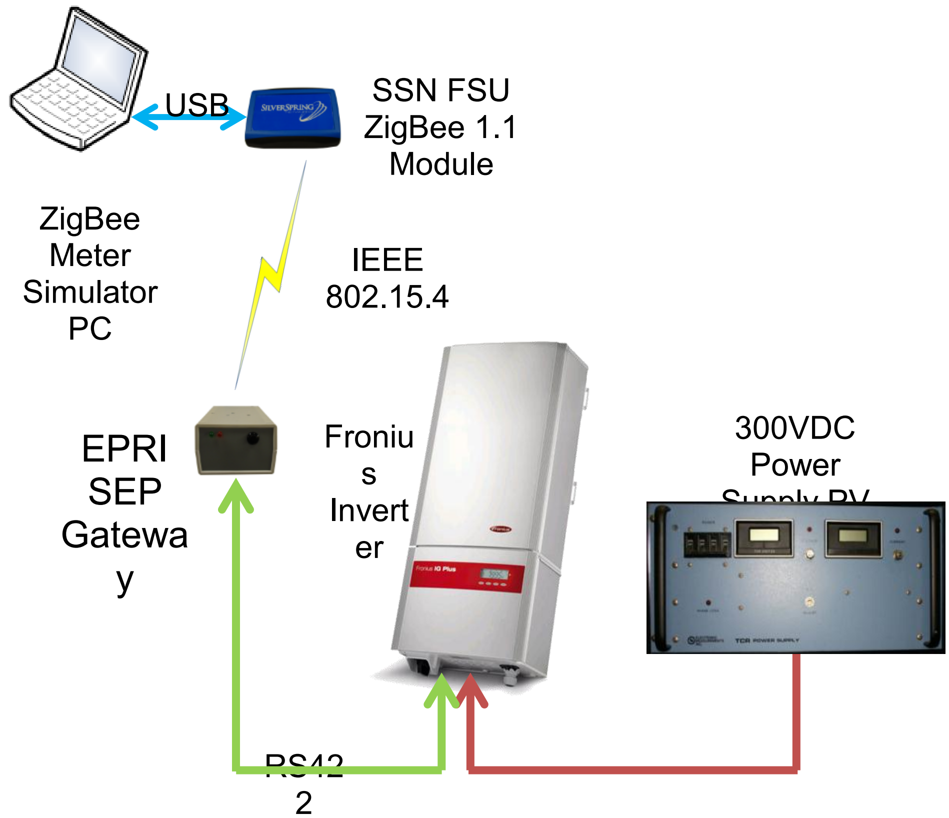

Figure 2-2
Testing at EPRI Knoxville Laboratory

Table 2-1 provides a detailed list of the equipment used for the demonstration tests.

Table 2-1
Equipment List

Device	Description
Inverter	Fronius IG Plus V 3.0-1 UNI rated at 3kW PV with maximum power handling capability of 4kW
DC Power Supply	TRC Model TCR500T20-1 capable of 500VDC at 20 amperes maximum
SEP Gateway	Device constructed by EPRI to perform protocol translation between ZigBee 1.1 to the Fronius interface protocol
Electrical Meter	Landis and Gyr Focus AX with Silver Spring Networks NIC, FW version UtilOS v2.10.6c
Headend System	Silver Spring Networks UtilityIQ v4.2.14
Headend System	Silver Spring Networks HAN Communication Manager v1.7.2
SSN FSU	Silver Spring Networks HAN Test Kit

SEP Communications

The test is designed to use the currently deployed hardware and software used by SMUD as shown in Figure 2-1. A key element of this demonstration is the repurposing of SEP 1 DRLC and metering functions to be used for control and monitoring of smart inverters.

Device Join

Low level communication between the gateway and the meter is handled by the ZigBee protocol as outlined in ZigBee document 1_053474r17ZB_TSC-ZigBee-Specification.pdf. Creating the ZigBee network or "joining" the meter and gateway is handled in hardware by placing the both devices in join mode. Once the network is formed, the devices can exchange application layer messages.

Device Operation

Application layer messages follow the Smart Energy Profile (SEP) version 1.1 which defines the DRLC and Metering clusters. SEP is defined in the ZigBee document 084956r05ZB_ZSE-Smart_Energy_Specification_Package.pdf. SEP uses and extends the standard ZigBee clusters defined in the document 075366r01ZB_AFG-ZigBee_Cluster_Library_Public_download_version.pdf. All of these documents are available for download at http://www.zigbee.org.

The gateway polls the Fronius inverter every 5 seconds, alternating between reading watts (W) and total watt-hours (Wh). It creates 15 minute intervals that can be read via the ZigBee simple metering cluster. The current implementation only reports one interval at a time, regardless of how many intervals are requested. The previous 24 intervals are stored and can be queried one at a time.

On startup, the gateway sets the inverter to 100% generation. If the connection to the ZigBee network is lost and an event is in progress, the inverter generation reverts to 100% output.

When an inverter output reduction is desired, a DRLC event is sent to the SEP Gateway. To control the amount of generation, the duty cycle parameter in the DRLC message is set to control percentage output. Acceptable values are between 0 and 100% with 100% being full output from the inverter. Any power request below 10% is treated as a shutdown by the Fronius inverter. This is a function of the inverter and not the EPRI gateway module.

The gateway implements the simple metering and DRLC clusters from ZigBee 1.1. Data read from the inverter are in watts, while the ZigBee network expects an integer value in kW. To prevent losing precision due to rounding, the readings from the inverter are reported in watts and the appropriate metering divisors are set to 1000. This is the normal method used by SEP 1.1 to maintain reading accuracy when dealing with a wide range of returned values.

The gateway can connect to a computer via a USB connector for purposes of accessing debug messages generated during the test process. It provides information on the ZigBee connection status, power generated by the inverter and message logging for events.

Processing DRLC Events

When the gateway boots or connects to a ZigBee network, it first performs time synchronization, and then queries for active events. It only stores one event at a time. When an event ends or is canceled, the device will query for another event. If the ZigBee network connection is lost, any stored events are cleared, and any in progress events are canceled.

Processing Simple Metering Queries

The gateway responds to load profile requests, but will only return one interval at a time in 15 minute intervals.

The gateway is capable of supporting the following attributes from the SEP 1.x metering cluster:

- Summation delivered (0x0000)
- Summation received (0x0001)
- Instantaneous demand (0x0400)
- Unit of measure (0x0300)
- Divisor (0x0302)
- Summation formatting (0x0303)
- Demand formatting (0x0304)
- Metering device type (0x0306)

See the ZigBee Smart Energy Profile Specification, document 075356r16ZB, starting on page 158 for a description of these attribute/reading information set identifiers. These values would be defined in the gateway for fixed values of read from the inverter for measured values such as Instantaneous demand. The data can then be reported to the SSN headend using the metering cluster.

Time Synchronization

Upon joining a ZigBee network, the gateway queries the network for the current time. Time synchronization is repeated every hour thereafter.

Inverter Communications

Two control functions were implemented; output limiting as a percentage of maximum output and inverter shutdown. A single control message provides functionality to set the output level to a desired percentage of maximum or shut the inverter down completely. The output level can be set to any value between 10 and 100 percent of maximum output. Any request to limit the output to less than 10% of the maximum will result in an inverter shutdown.

Two monitoring functions were implemented:

- **Historical Meter Data** – This provides the amount of PV power generated in fifteen minutes blocks.
- **Instantaneous Power** – This provides the amount of PV power being generated at the instant that the request was received.

The Fronius IG Plus V inverter communicates via a proprietary Fronius interface protocol running over a full duplex RS422 connection. This protocol is described in detail in 42_0410_1564_168027_snapshot.pdf available from Fronius.

For this demonstration, only three basic functions were used. The first two are the ‘Get power – Now’ command to read the instantaneous power and the ‘Get energy – Total’ to read the total watt hours produced. These were used for the monitoring functions described above. The ‘Set Power Reduction’ function was used to limit the output power and to shut down the inverter.

3
TEST EQUIPMENT ARRANGEMENT

Inverter Power Connection Details

Figure 3-1 shows a simplified power wiring diagram for the test configuration.

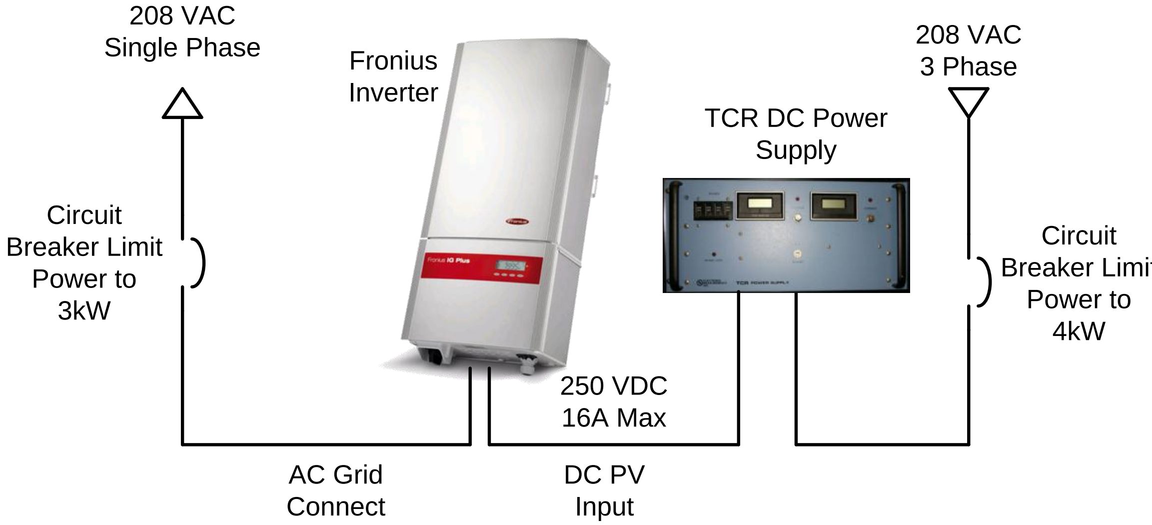

Figure 3-1
Power Wiring Diagram

The inverter was connected to the grid via a single phase 208VAC 60Hz tie into a panel through a breaker to limit the maximum power supplied to approximately 3kW. The PV supply was simulated by a DC power supply. This DC supply is connected to a 3 phase 208 VAC source via a circuit breaker limiting maximum power to 4kW.

Figure 3-2 shows the inverter lying on top of the power supply cart. All testing was done in this configuration.

Figure 3-2
Inverter and DC Power Supply

The wiring terminal block is visible at the end of the inverter facing the camera. The first is a view inside through the open lid and the second is from the bottom looking in through the wire exit. The bottom cable plate has been removed for a clear view of the terminations.

Figure 3-3 shows the unit after connection. The grid connection is in the bottom right of the image below in the order ground, L1, L2, and neutral. The blue wire above the grid connection is the RS422 communications cable. The black cable to the left of the grid connection is the plus and minus of the DC power supply.

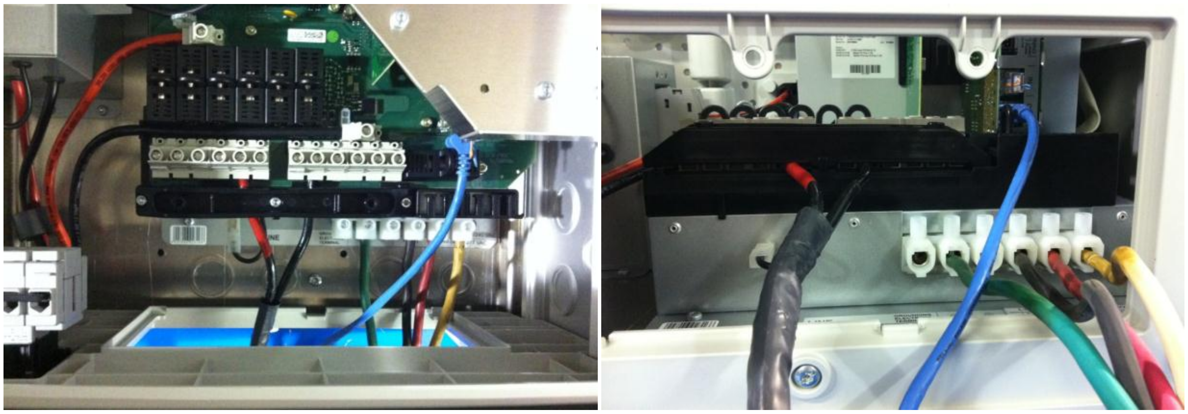

Figure 3-3
Inverter with Power and Communication Connections

Testing Performed at SMUD

The testing performed at SMUD was done using 208VAC phase to phase with neutral and ground for the grid connection. The SEP message source was Silver Spring Networks UtilityIQ v4.2.14 communication through a Landis and Gyr Focus AX electric meter with Silver Spring Networks NIC, FW version UtilOS v2.10.6c. Test certificates were used for all steps.

The test steps performed were power limiting and inverter shut down.

Testing Performed at EPRI

The testing performed at EPRI was done using 240VAC split phase with neutral and ground for the grid connection. The SEP message source was Silver Spring Networks simulator system using a Linux application to generate messages. Test certificates were used for all steps.

The test steps performed were historical data collection and instantaneous power acquisition.

4
TEST RESULTS

SMUD

The field test was conducted at SMUD on April 23. The steps from the test plan and the results matrix are presented below.

Test Plan

Step 1 – Device Registration

Equipment Setup:

1. Make sure the ZigBee network and the EPRI SEP Gateway are programmed with the same link key. The link key is a 16 byte hex string. It's currently hard coded to 1 followed by 15 zeros.
2. With the equipment connected as shown in the architecture drawing, connect the inverter to the grid power of 240VAC.
3. Connect the SEP Gateway to the Arduino monitor PC using the USB cable.
4. After setting the output voltage and current limit to minimum, turn on the power switch on the TRC DC power supply.
5. Increase the current limit one-half rotation on the DC power supply.
6. Increase the voltage adjustment until 270 VDC is achieved. The Fronius inverter display will show the startup sequence which takes approximately two minutes.
7. Slowly increase the current limit until the Fronius inverter displays 2000 to 2500 watts. Pause to allow reading to stabilize.

Test Sequence:

Place the router or the coordinator of the ZigBee network in join mode through the HAN Communication Manager head-end application.

Momentarily press the button on the SEP Gateway. The red LED should flash, indicating that the button was pressed. Wait for 30 seconds for the device to join the network. Upon successfully joining a network, the green LED will blink.

If the device has not joined the network after 30 seconds, restart the join mode on the coordinator and press the button on the SEP Gateway. Wait for 30 seconds.

If the second attempt fails, restart the join mode on the coordinator and press and hold the button the SEP Gateway for 5 seconds. Wait 30 seconds.

☐ Pass ☐ Fail

Step 2 – Set Inverter Output Level to 25%

Equipment Setup:

No changes from the conclusion of step 1 above.

Test Sequence:

Send the DRLC message:

```
d = m.nm_han_create_drlc(:dur=>10, :heat_off=>20, :crit=>5, :duty_cycle=>25)
```

This will create an event that starts now, has a duration of 10 minutes, and limits the inverter to 25% of maximum generation. The red light on the SEP Gateway will turn on. The power output displayed on the Fronius inverter will now read approximately 1000 watts.

☐ Pass ☐ Fail

Step 3 – Cancel the Output Reduction Event

Equipment Setup:

No changes from the conclusion of step 2 above.

Test Sequence:

While the event from step 2 is still active, send the DRLC cancel event:

d.cancel

The red light on the SEP Gateway will turn off. The power output displayed on the Fronius inverter will now revert to approximately the same value as in step 1.

Note: the following command will cancel all active events:

m.nm_han_cancel_all_drlc_events

If any event is in progress, this should turn the red light on the SEP Gateway.

☐ Pass ☐ Fail

Step 4 – Set Inverter Output Level to 0%

Equipment Setup:

No changes from the conclusion of step 3 above.

Test Sequence:

Send the DRLC message:

d = m.nm_han_create_drlc(:dur=>10, :heat_off=>20, :crit=>5, :duty_cycle=>0)

This will create an event that starts now, has a duration of 10 minutes, and limits the inverter to 0% of maximum generation. The red light on the SEP Gateway will turn on. The power output displayed on the Fronius inverter will now read approximately 0 watts.

☐ Pass ☐ Fail

Step 5 – Cancel the Output Reduction Event

Equipment Setup:

No changes from the conclusion of step 4 above.

Test Sequence:

While the event from step 4 is still active, send the DRLC cancel event:

d.cancel

The red light on the SEP Gateway will turn off. The power output displayed on the Fronius inverter will now revert to approximately the same value as in step 1. Note that the output will require the normal startup cycle time after the unit restarts.

Note: the following command will cancel all active events:

m.nm_han_cancel_all_drlc_events

If any event is in progress, this should turn the red light on the SEP Gateway.

☐ Pass ☐ Fail

Test Results

The test results are organized with the "Test" column in the format:

duty cycle – test # - date of test

Table 4-1
SMUD Test Results

Test	Result	Log File?	Notes
25%-2A-4/23	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 25%. After test finished inverter showed "DC side low" and went into a 2 minute delayed start up mode. The HAN communication manager (HCM) program didn't register a completed message immediately. The HCM program has a significant time delay to register a completed message.
25%-2B-4/23	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 25%. Inverter returned to 1.5 kW with no issues. HCM program didn't register a completed message immediately. The HCM program has a significant time delay to register a completed message.

Test	Result	Log File?	Notes
25%-2C-4/23	Pass	No	Inverter and gateway received signal. Inverter adjusted output power level to 25%. After test finished inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program didn't register a completed message immediately. The HCM program has a significant time delay to register a completed message.
25%-2D-4/23	Pass	No	Inverter and gateway received signal. Inverter adjusted output power level to 25%. Inverter returned to 1.5 kW with no issues. HCM program didn't register a completed message immediately. The HCM program has a significant time delay to register a completed message.
25%-3A-4/23 Cancel	Pass	No	Inverter and gateway received signal. Inverter adjusted output power level to 25%. After signal was canceled inverter responded normally. HCM program registered a cancellation immediately.
25%-3B-4/23 Cancel	Pass	No	Inverter and gateway received signal. Inverter adjusted output power level to 25%. After signal was canceled inverter responded, but didn't return to normal. Inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program registered a cancellation immediately.
25%-3C-4/23 Cancel	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 25%. After signal was canceled inverter responded, but didn't return to normal. Inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program registered a cancellation immediately.
25%-3D-4/23 Cancel	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 25%. After signal was canceled inverter responded, but didn't return to normal. Inverter showed "DC side low" and went into a 2 minute delayed start up mode, and then later showed "State 556" error code. HCM program registered a cancellation immediately.
25%-3E-4/23 Cancel	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 25%. After signal was canceled inverter responded, but didn't return to normal. Inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program registered a cancellation immediately.
0%-4A-4/23	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 0%. After the even ended the inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program didn't display that the event completed immediately. The HCM program has a significant time delay to register a completed message.
0%-4B-4/23	Pass	No	Inverter and gateway received signal. Inverter adjusted output power level to 0%. After the even ended the inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program didn't display that the event completed immediately. The HCM program has a significant time delay to register a completed message.
0%-4C-4/23	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 0%. After the even ended the inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program didn't display that the event completed immediately. The HCM program has a significant time delay to register a completed message.

Test	Result	Log File?	Notes
0%-4D-4/23	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 0%. After the even ended the inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program didn't display that the event completed immediately. The HCM program has a significant time delay to register a completed message.
0%-5A-4/23 Cancel	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 0%. After the even ended the inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program registered a cancellation immediately.
0%-5B-4/23 Cancel	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 0%. After the even ended the inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program registered a cancellation immediately.
0%-5C-4/23 Cancel	Pass	Yes	Inverter and gateway received signal. Inverter adjusted output power level to 0%. After the even ended the inverter showed "DC side low" and went into a 2 minute delayed start up mode. HCM program registered a cancellation immediately.

Images of Test Results

Figure 4-1
Pre-event Conditions of 25%-2A-4/23: Inverter Registering at 1553 Watts and Power Supply Provides Stable Power

This will create an event that starts now, has a duration of 10 minutes, and limits the inverter to 0% of maximum generation. The red light on the SEP Gateway will turn on. The power output displayed on the Fronius inverter will now read approximately 0 watts.

Figure 4-2
Event Conditions of 25%-2A-4/23: EPRI SEP Gateway Registers Signal with the Red-light Indicator

Figure 4-3
Event Conditions of 25%-2A-4/23: Inverter Generation Reduced to 1008 Watts and the Power Supply is Displaying Lower Amperage

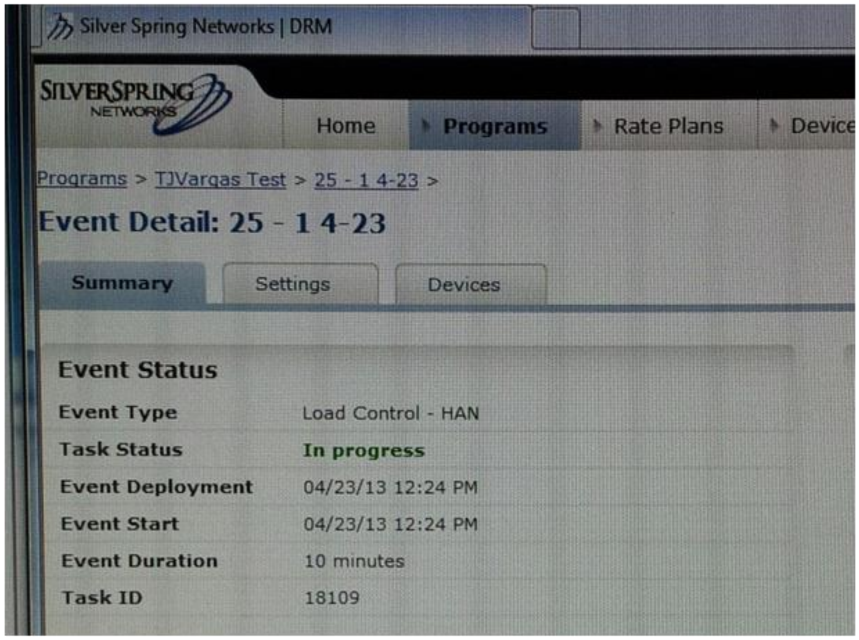

Figure 4-4
Event Conditions of 25%-2A-4/23: The HCM Registers that the Event is Occurring

EPRI

The meter data sections of the test were conducted at the EPRI Knoxville facility on May 30. The steps from the test plan and the results matrix are presented below.

Test Plan

Step 6 – Read Attributes

Equipment Setup:

The EPRI SEP Gateway will be joined to the network and communicating as proven by reducing the inverter output to 50% and returning it to full output.

Test Sequence:

Conduct the test as described in the section titled Reading Attributes and Load Profile Data in the SEP Gateway Manual. Screen shots will be taken at each step during the process to document the results and provide to SMUD.

Step 7 – Read Load Profile Data

Equipment Setup:

No changes from the conclusion of step 6 above.

Test Sequence:

Conduct the test as described in the section titled Reading Attributes and Load Profile Data in the SEP Gateway Manual. Screen shots will be taken at each step during the process to document the results and provide to SMUD.

Test Results

The test results are organized with the "Test" column in the format:

test # - date of test

Table 4-2
EPRI Test Results

Test	Result	Log File?	Notes
6A-5/30	Pass	Yes	Gateway received the request for power level and returned data records. The returned value was 2037 watts which roughly matched the display on the inverter screen which varied between 2000 and 2200 watts.
6B-5/30	Pass	Yes	Gateway received the request for power level and returned data records. The returned value was 2013 watts which roughly matched the display on the inverter screen which varied between 2000 and 2200 watts.
7A-5/30	Pass	No	Gateway received the request for the most current historical record and returned data records. The returned value was 527 watt-hours which roughly matched the display on the inverter screen which varied between 2000 and 2200 watts over 15 minutes. Record time was (423236704 seconds past January 1, 2000) Thursday, 30 May 2013 13:45:04 UTC which matched the time of the test.
7B-5/30	Pass	No	Waited 15 minutes and repeated the request. Gateway received the request for the most current historical record and returned data records. The returned value was 526 watt-hours which roughly matched the display on the inverter screen which varied between 2000 and 2200 watts over 15 minutes. Record time was (423237608 seconds past January 1, 2000) Thursday, 30 May 2013 14:00:08 UTC which matched the time of the test.

5 OUTCOME

There were no significant issues in using SEP 1.1 to control a smart inverter by re-purposing the DRLC and meter reading functions. In this case, the duty cycle value was used to contain the percent output where 100% was the maximum output from the inverter.

After an initial successful join of the Gateway, some connection issues were encountered after this join was lost. This issues were resolved after the HCM was forced to un-join from the meter and Gateway. After forcing the un-join the Gateway and the meter joined without problems.

The inverter was constantly searching for the optimum power output from the solar panels. Because a DC power supply used as a simulated solar source, the power output of the inverter was not steady and varied by up to 200 watts. With this taken into consideration, the values returned were well within expected accuracy.

This was a test of communications and as such the results were positive. Power output from the inverter was limited to 2000 watts while at SMUD because of the use of a 208VAC grid connection combined with a DC power supply used to simulate a PV array. When this inverter was used at the EPRI laboratory driven by a commercial solar simulator, the full power range of the inverter up to 4000 watts was available.

During the testing the inverter would occasionally display “DC side low" when a DRLC event ended. This seems to be an issue of using a DC power supply for the simulated PV input. This was never an issue when testing in the Knoxville Laboratory using a commercial PV simulator or actual PV panels as a power source. This is likely caused by the DC supply not responding quick enough causing the inverter went into a restart mode. This has no impact on the success of the communication test since there is a high level of confidence that the system will operate normally with PV power source.

As a proof of concept, this demonstration verified there are no technical issues to prevent the control of smart inverters using the DRLC and metering commands built into SEP 1.1. This demonstration did not address the operational issues that would be encountered re-purposing these commands.

6
IMPLICATIONS FOR WIDESPREAD DEPLOYMENT

One of the objectives of this research was to improve understanding of the capabilities, advantages, and limitations of using the in-place AMI network to accomplish communications and control functions with a widespread deployment of smart residential PV inverters.

Cost Implications of AMI Network Smart Inverter Communications

Some of the advantages of this approach were understood at the outset, primarily that the communications infrastructure had already been paid for and deployed through SMUD's SmartGrid project, and as such, so long as inverter communications did not overwhelm the system capacity, infrastructure costs would be minimal. As envisioned, the only hardware to enable inverter communications would be a ZigBee compatible device in the form of either the inverter itself with an embedded chip, or a gateway as demonstrated in this project. As a result, achieving broad communications with residential inverters could be inherently low cost given the expected costs of the ZigBee chips themselves are expected to be on the order of a few dollars per unit.

Other advantages lending themselves to this approach were the interfaces that have been developed to support Demand Response functionality that can be leveraged for communicating with inverters using the same protocols, namely SEP. In addition, tools are in place with SSN such as UIQ, for communicating with thermostats and other in-home devices that make use of the SEP standard, that offer scheduled and real-time 2-way communications with many thousands of devices at once. These systems currently talk to our meters on regular polling schedules, typically every 4 hours for residential customers, and more frequently for commercial to collect usage data. They are also used for service shut-offs and other demonstration project purposes at this point. Finally, mesh network offers some inherent reliability due to redundancy of the communications pathways afforded in a mesh. Typically if meters are attempted to be reached 3 times by a single Wireless Access Point (WAP), and then are attempted from a neighboring WAP 3 times. Communications rates for SMUD's meters through the SSN network are currently 97% on the first attempt, and 99.9% for an entire 3 minute cycle of 6 reads from 2 different WAPs.

Functionality Considerations

In terms of the capabilities, the demonstration itself was limited to the functions that were able to be supported by SEP 1.1 and the DRLC. As such the functions were limited to curtailment and monitoring functions and did not include any of the more advanced voltage control and storage related functions that are supported in SEP 2.0. Once SEP 2.0 is deployed on SMUD's AMI network however, it is expected that these and other functions will be supported. Beyond the specific functions, the demonstration showed fast and reliable response to the control signals that were sent, typically seeing response by the inverter on the order of 1-3 seconds after a command was sent. This responsiveness is impressive considering the signal was routed through the web and the SSN servers in San Diego, back up through SMUD's Wireless Access Point, through the meter and Gateway to the inverter. Such responsiveness suggests the potential for real-time command signals to be sent out that could affect changes on a system in response to very short-term needs of a utility related to unexpected or forecasted changes in available generation or significant swings in demand.

However, consideration also needs to be made for the IT constraints associated with scheduling events with such high frequency. The UIQ system was not designed for broad communication and execution of different functions on a minute to minute basis with hundreds of WAPs. Based on discussion with SSN representatives, such levels of communication would likely overwhelm some of the design constraints of the UIQ system, and they were much more comfortable with a time frequency closer to 5 minutes relative to the capabilities of the system.

Security Considerations

Despite the apparent advantages from a cost and functionality standpoint for achieving relatively high frequency, reliable communication with potentially 10's of thousands of devices, there are undoubtedly security considerations that need to be addressed with this approach. For any device connecting to the network, separate testing for compatibility with Silver Springs Network and Zigbee must be done. For any upgrades to the inverter firmware, re-testing would need to occur to ensure compatibility and security requirements are maintained. Currently, costs for these tests are on the order of $20,000 per test, which is potentially cost-prohibitive without significant scale in the number of devices that would be deployed. Such considerations make it difficult to envision a system where 10's of manufacturers of devices were able to maintain up to date testing and security requirements without significantly adding to the costs of devices. However, promising approaches are being approached by EPRI to make use of a common interface gateway that would enable communications with a variety of consumer appliances and would effectively enable a single device to be tested and used for communications in each utility smart grid deployment. SMUD is pursuing demonstration of this type of a product with EPRI and others to reduce concerns about costs of meeting security requirements, and generally reduce the costs associated with enabling utility communication with a variety of consumer devices.

Bandwidth, Latency, and other Potential Limitations

Another potential disadvantage of this approach is that the nature of the mesh network as designed does not assure certainty of delivery of control signals. Generally, this effect gets worse as the number of devices per WAP increases and as the time frequency of communication decreases. Currently SMUD's system is designed fairly conservatively, with approximately 5,000 devices per WAP, which enables the system to achieve 97% communications success rate on the initial attempt, and 99.9% after the 6^{th} attempt, which occurs in a 3-minute cycle. According to SSN, typically 95% of the devices receive a signal within about 1 second on the system. The system makes use of approximately 50% of its theoretical capacity for the first 20 to 30 minutes of a 4 hour read cycle, with the majority of that amount being taken up by protocol overhead. The PV transactions would not be expected to increase the overhead, and would have a comparable impact as the metering transactions, which as noted above is quite small. As a result, it is expected by SSN that the addition of up to 50,000 PV inverter devices ($1/10^{th}$ the number of existing meter devices), communicating at 50X the frequency (every 5 minutes as opposed to every 4 hours), and passing 3 to 5 data points per communication, would not have a significant impact on the system bandwidth.

In the event that issues are identified with unacceptable levels of failed communications, addition of WAPs to the system would alleviate congestion and enable higher communications rates. Generally, costs for additional WAPs are dominated by design and installation costs rather than hardware costs, and in total may range from $7K to $12K installed, with an additional $30 -50 per month wireless fee. Conditions where an additional access point might be required are only anticipated to occur in large communities with very high penetrations of solar homes. While potential bandwidth and latency constraints can be addressed by deployment of additional WAPs on the network, valuation of achieving higher certainty of receipt of signals by all units compared to the cost of the additional WAP's has not been done, and requires far more information about the value of services that could be provided by the PV devices than is available today. Theoretical exploration of this will require extensive further research, including valuation under various scenarios of scaled deployments and considering a variety of control functionality that might be desired. Alternatives to deal with this issue are to develop and deploy localized control schemes at the inverter that can be selected periodically by the utility to address concerns related to variability, voltage control or back-feeding of the substation, which may prove more cost-effective than enhancements to the AMI network. In addition, these localized control strategies are likely to be more desirable to system operators given the complexity of coordinating tens of thousands of small units on a high frequency basis.

Summary and Other Considerations

Based on discussion with internal SMUD staff and SSN staff it does not appear that anticipated high penetration PV scenarios currently contemplated present any significant challenge to the existing network performance. Security issues may be a challenge to address but are likely substantially mitigated by moving to a standardized multi-appliance gateway device for the interface. In the event extremely high penetrations in certain communities do impact performance, additional WAPs can be added at a reasonable cost. Finally, expected autonomous modes may substantially reduce the potential system demands currently being contemplated, rendering even high penetration scenarios extremely unlikely to tax the existing system architecture.

Beyond the approach explored in this research, additional evaluation of alternative pathways such as broadband should be explored to understand advantages and limitations of those pathways. In particular as microinverters begin to take up a larger share of the residential inverter market, broadband communication with PV inverters or residential gateways may become much more commonplace, and as such might lend itself to being a preferred pathway for devices that may have a lower price point than 'centralized' residential inverters. Some of the perceived limitations of a broadband approach is the lack of a single utility control interface through which devices from a variety of manufacturers could be accessed and controlled, as well as challenges with maintaining or controlling connectivity to the devices, and the potential for increased costs for the services that are enabled by the broadband provider, the router, and the PV inverter supplier. On the other hand, a single-point utility-PV broadband interface could certainly be developed if such a communications pathway presented enough advantages.

A

EPRI SEP 1.1 GATEWAY IMPLEMENTATION

One of EPRI's roles in this demonstration was the development of a SEP 1.1 gateway to translate the messages into the language that the Fronius inverter understands. This was accomplished using an Arduino Mega 2560 development board combined with an XBee Pro S2B module for communication with the Silver Spring Network devices and RS485 boards for the link to the Fronius inverter.

Smart Energy Profile 1.0 does not support inverter control for solar panels, wind turbines, or battery systems, yet it is implemented by several utilities. By repurposing aspects of the demand response load control (DRLC) event and metering commands it is possible to effectively control a smart inverter.

For this demonstration, a limited set of functions were required, including:

1. Real power output control
2. Inverter shutdown
3. Instantaneous power output monitoring*
4. KWH output history*

(*Note that instantaneous power output monitoring and kWh output history were tested in EPRI lab only due to limited availability of SMUD Smart Grid support staff to troubleshoot and ensure successful testing of these functions in SMUD lab)

The Fronius IG Plus V smart inverter was chosen to be the end device. It had the capability to perform all of the above functions and many more if needed for expansion of the demonstration. Fronius uses a well documented proprietary protocol connecting over full duplex RS422.

The SEP Gateway was implemented using an Arduino Mega 2560 single board computer. Figure A-1 shows the components of the EPRI SEP Gateway.

An XBee board provides the interface for the ZigBee messages received from the meter or SSN simulator. The CPU translates the request into the Fronius message format to implement the requested control function or data request. Two RS485 boards translate the TTL serial streams to RS422 full duplex required by the inverter.

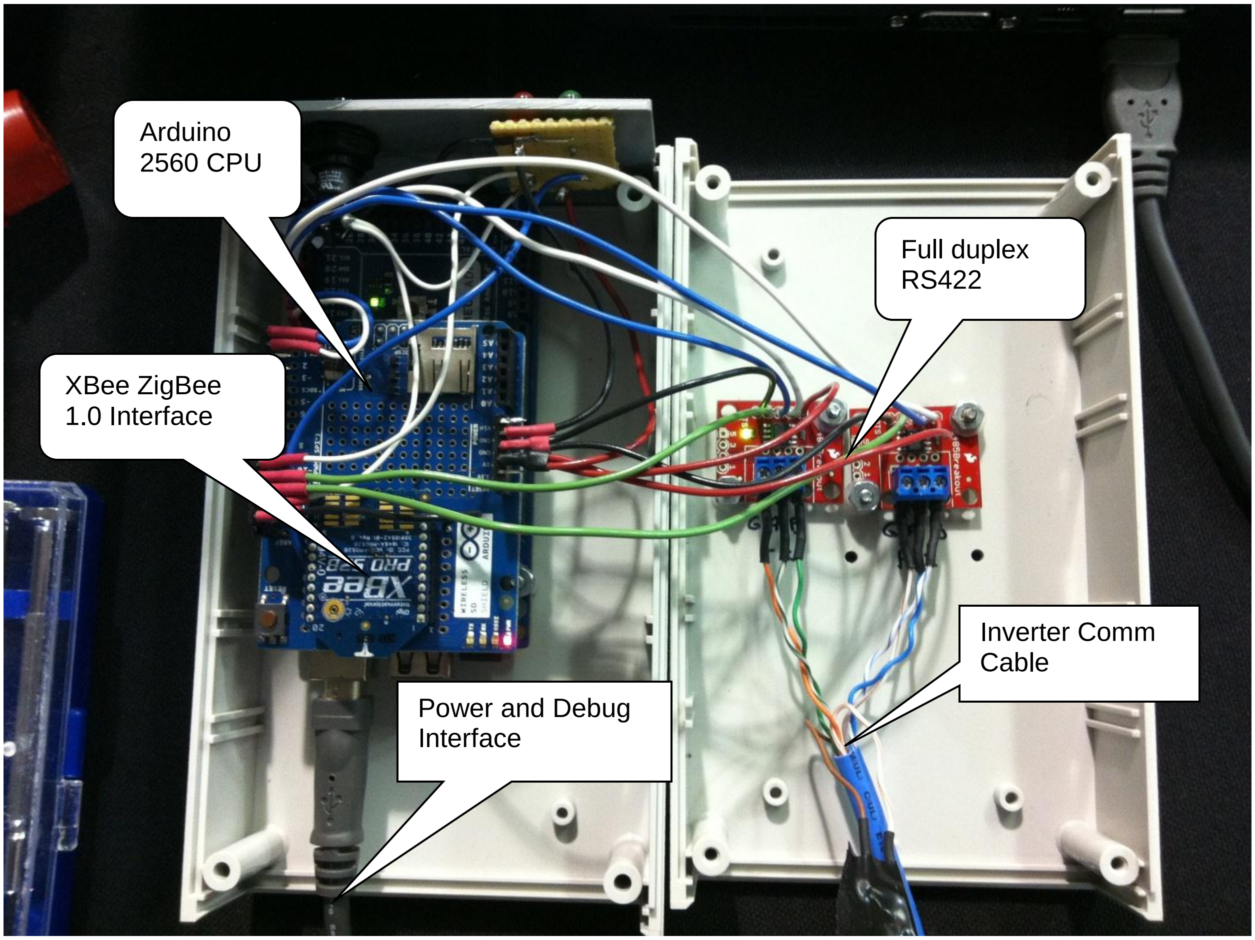

Figure A-1
EPRI SEP Gateway Internal Components

Figure A-2 shows the schematic for the EPRI SEP Gateway.

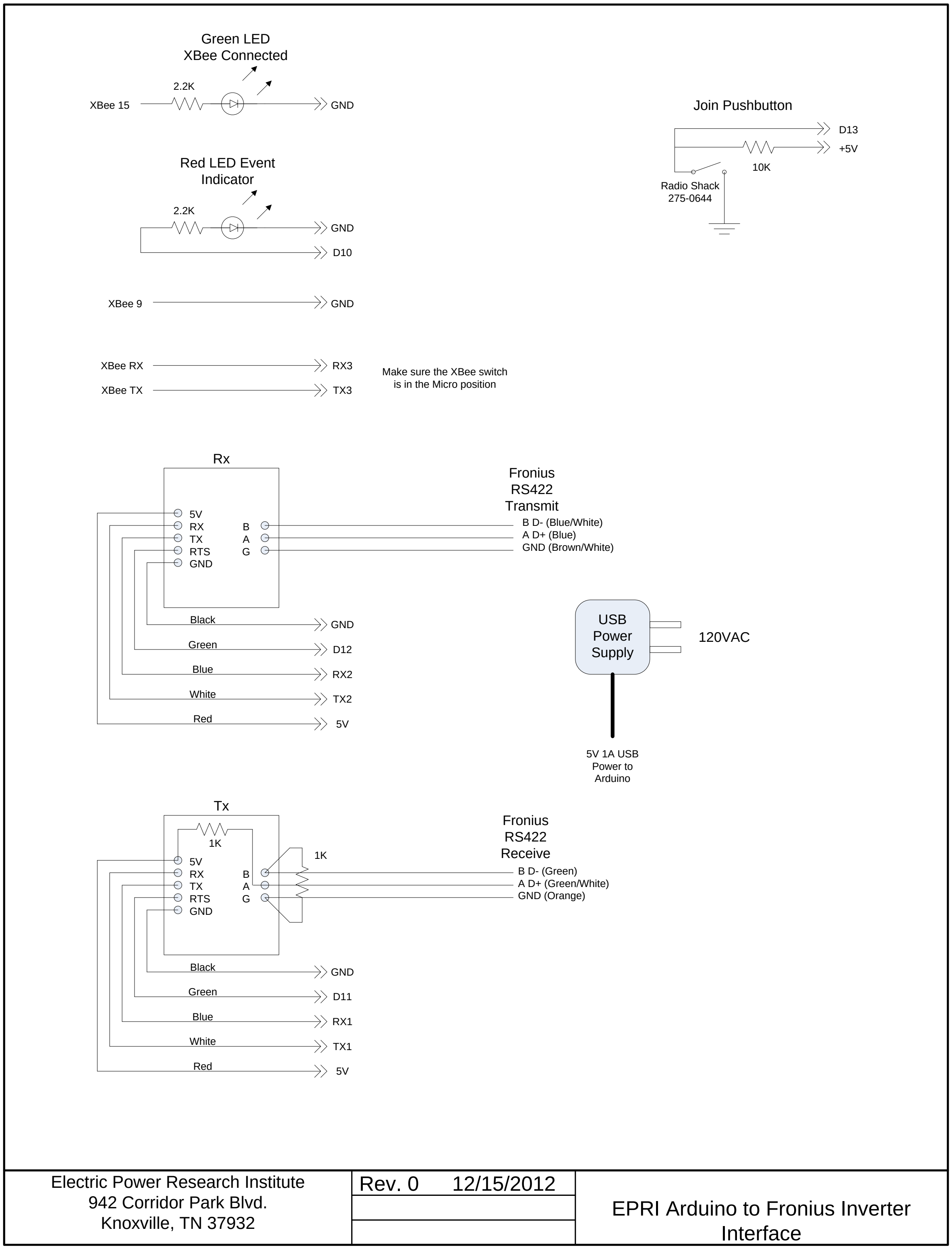

Figure A-2
SEP Gateway Schematic

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com