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Solar Energy Grid Integration Systems:
Final Report of the Princeton Power Systems Development of the 100kW Demand Response Inverter

Ward Bower, Sigifredo Gonzalez, Abbas Akhil, Lisa Sena-Henderson, Carolyn David, Mark Holveck, Darren Hammell, Paul Heavener

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Solar Energy Grid Integration Systems:
Final Report of the Princeton Power Systems, Inc. Development of the 100kW Demand Response Inverter (DRI)

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Abstract

Initiated in 2008, the Solar Energy Grid Integration (SEGIS) program is a partnership involving the U.S. Department of Energy, Sandia National Laboratories, electric utilities, academic institutions and the private sector. Recognizing the need to diversify the nation's energy portfolio, the SEGIS effort focuses on specific technologies needed to facilitate the integration of large-scale solar power generation into the nation's power grid Sandia National Laboratories (SNL) awarded a contract to Princeton Power Systems, Inc., (PPS) to develop a 100kW Advanced AC-link SEGIS inverter prototype under the Department of Energy Solar Energy Technologies Program for near-term commercial applications. This SEGIS initiative emphasizes the development of advanced inverters, controllers, communications and other balance-of-system components for photovoltaic (PV) distributed power applications. The SEGIS Stage 3 Contract was awarded to PPS on July 28, 2010. PPS developed and implemented a Demand Response Inverter (DRI) during this three-stage program. PPS prepared a "Site Demonstration Conference" that was held on September 28, 2011, to showcase the cumulative advancements. This demo of the commercial product will be followed by Underwriters Laboratories, Inc., certification by the fourth quarter of 2011, and simultaneously the customer launch and commercial production sometime in late 2011 or early 2012. This final report provides an overview of all three stages and a full-length reporting of activities and accomplishments in Stage 3.

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NOMENCLATURE

BOS	Balance of System
COTS	Commercial off the Shelf
CRL	Central Resonant Link
DG	Distributed Generation
DOE	Department of Energy
DR	Demand Response
DRI	Demand Response Inverter
EMI	Electro-magnetic Interference
EV	Electric Vehicle
FAT	Factory Acceptance Test
GTIB	Grid Tied Inverter w/ Battery
GTI	Grid Tie Inverter
HMI	Human Machine Interface
IGBT	Insulated Gate Bipolar Transistor
LCOE	Levelized Cost of Energy
MAF	Materials acceptance Form
MPPT	Maximum Power Point Tracking
NOC	Network Operations Center
NREL	National Renewable Energy Laboratories
PCB	Printed Circuit Board
PJM	Pennsylvania, New Jersey, and Maryland Interconnection
PPS	Princeton Power Systems, Inc.
PQA	Power Quality Analyzer
PSE&G	Public Service Electric and Gas
PV	Photovoltaic
QA	Quality Assurance
RMA	Returned Material Authorization
ROI	Return On Investment
SA	Standalone
SAM	Solar Advisor Model
SBC	Single Board Computer
SCADA	Supervisory Control and Data Acquisition
SEGIS	Solar Energy Grid Integration Systems
SETP	Solar Energy Technologies Program
SNL	Sandia National Laboratories
SOC	State of Charge
SPL	Sound Pressure Level
UUT	Unit Under Test
VAR	Volt Amperes Reactive
VRLA	Valve Regulated Lead Acid
VSD	Variable Speed Drive

1. EXECUTIVE SUMMARY

Initiated in 2008, the Solar Energy Grid Integration Systems (SEGIS) program is a partnership involving the U.S. Department of Energy, Sandia National Laboratories, electric utilities, academic institutions, and the private sector. Recognizing the need to diversify the nation's energy portfolio, the SEGIS effort focuses on specific technologies needed to facilitate the integration of large-scale solar power generation into the nation's electric power grid.[1][2]

Sandia National Laboratories (SNL) awarded a Solar Energy Grid Integration Systems (SEGIS) [1] Stage 3 contract to Princeton Power Systems, Inc. (PPS), to commercialize a 100kW Demand Response Inverter (DRI). The SEGIS program emphasizes the development of advanced inverters, controllers, and other balance-of-system components for photovoltaic (PV) distributed power applications. In Stage 1, the feasibility, cost-effectiveness, and market analysis of the Demand Response Inverter concept was conducted. In Stage 2, PPS successfully developed 100kW DRI prototypes. The SEGIS Stage 3 contract was awarded to PPS on July 28, 2010. PPS has aggressively pursued this opportunity to commercialize its advanced DRI technology. The inverter is being field tested in various unique environments and applications to evaluate and demonstrate the reliability and cost-effectiveness of the system. PPS is planning to further beta test the DRI in the fourth quarter of 2011, and then get commercial certification and make the DRI available commercially for sale during the first quarter of 2012.

PPS has progressed on schedule on the commercialization of the DRI since the prototype development in Stage 2, which was completed in June 2010. The design for manufacturability, reliability, and audible noise, as well as the cost of the production units has been finalized and materials have been procured from key suppliers. Cost targets were established based on market-driven production requirements. Supplier and cost of goods analysis have been performed. Assembly and test facilities have been upgraded for the pilot production run. Test plans have been developed for certification and for environmental, life cycle and demonstration testing.

The pilot production DRI assembly began during the month of May 2011. Beta testing of the initial pilot units is now underway. The certification testing started in October and is expected be completed during the first quarter 2012. Marketing launch efforts are well under way. Strategic partnerships have been built with utilities, power solution providers, and users such as cities and education institutes.

PPS remains confident that the DRI will provide commercially viable PV interface systems that improve power quality and facilitate enhancement to the utility grid reliability. The controller is modular (it can be enlarged or modified) and integrates many balance-of-system (BOS) elements to optimize value and minimize installation/commissioning cost and complexity. The DRI is designed to communicate with utility energy portals (including smart metering systems) and with stand-alone energy management systems. The DRI's innovative design modularity and the use of commercial off the shelf (COTS) parts provide higher operating efficiency, improved reliability, and reduced cost and grid-support functionality to lower the levelized cost of energy (LCOE) and maximize value for "behind the meter" solar energy systems.

This final report provides details of progress made since the Stage 3 contract award, and the status of the project as of Sept 29, 2011. Required testing information and resulting Stage 3 improvements are included. An overview of Stage 1 and Stage 2 is included for completeness of the project.

2. INTRODUCTION

The Solar Energy Grid Integration Systems (SEGIS) [1] program is a part of the U.S. DOE Solar Energy Technologies Program (SETP), which has the objective of bringing the Levelized Cost of Energy (LCOE) of grid-interactive PV systems into parity with the electric grid, with reduced costs of PV Systems by 2015. A related objective of SEGIS is to show direct contributions to LCOE reduction through technology development that help to meet these goals. Hardware that results in a system LCOE of $.05-$.10/kWh is a high priority. Also, the DRI helps achieve the DOE $1/W Sunshot target for photovoltaic systems through the following:

High-frequency Controls (7kHz): The legacy converter operates at 2-3kHz of power device switching, resulting in a typical power density of $30kW/m^3$. Power densities are driven primarily by the harmonic filter components, which are bigger in order to keep harmonics below acceptable levels. Switching power devices at a higher frequency (6.5kHz) provided reduction in the sizes of these components, resulting in improvements in overall converter size and weight. The power density for the 100kW DRI with a 60Hz transformer at present is $60kW/m^3$. The reduction in size and weight has also reduced the converter acquisition and installation cost. Utilizing the Central Resonant Link in place of the 60Hz transformer will increase the power density even further.

High-frequency Controls (50kHz): Our SEGIS program explored pushing the control and switching frequency even higher, to 50kHz. Achieving this goal could reduce the size and cost of passive components even further. In the future, with the advancement of power semiconductor device technology (silicon carbide based devices) [2], it is feasible to switch the power devices at an even higher frequency. Further research in this area is required to achieve these goals, as limitations in the control system and triggering have been identified.

Internal Transformer Central Resonant Link (CRL) lowers BOS: The DRI is designed to have an integrated isolation transformer. This device is commonly used in industry to reduce installation time and cost, and reduce installed cost by eliminating cabling, conduits, and connections. The CRL takes this idea even further by providing a much smaller internal transformer ($.25m^3$ vs. $1.5m^3$) to further reduce the size of the inverter, the size of concrete pad-mounts, weight, and other BOS costs.

High-efficiency Transformer (CRL): The extremely high efficiency of the CRL transformer (99.8% peak efficiency, based on a Nanocrystalline ferrite core with litz wire windings) has been tested and demonstrated during Stage 2. Challenges remain to bring the manufactured cost down, and to build a supply chain to improve manufactured quality. Further, high efficiency reduces the size of the converter, reduces heat loss with associated costs and complexities, and increases energy yield from the solar array.

High Voltage for Lower Wiring Costs, Less Racking for Same Array Power: The internal transformers allow high voltage output without the additional cabling, size, and efficiency loss of external step-up transformers. As described above, the implementation of the CRL dramatically increases these benefits. Increased voltages on the PV side allow for lower wiring costs due to less copper, as well as higher cell efficiencies. Therefore, fewer panels are required to achieve the same power output, which leads to lower racking and installation costs. It also reduces space requirements, which reduces land leases and other installation and operating costs.

Safety Concerns—The Importance of Galvanic Isolation: DRI allows isolation from the grid the AC-link inverter incorporates a high-frequency isolation transformer into each of its four power ports. This is a critically important feature for making the inverter a universally compatible building block for any alternative energy system. By providing galvanic isolation between all ports, systems engineering can optimize the systems that are connected to each port without consideration of what is being connected on other ports. For instance, a grounded PV array can be connected to the DC port while a grounded-neutral AC power system is connected to the grid port. Without this isolation, an external isolation transformer would have to be installed to make these two systems compatible with each other. Similarly, the battery system can either be grounded or not, regardless of whether the PV system is grounded, and regardless of whether the AC power system is grounded, without requiring an isolation transformer. Another important example is the case of a multi-inverter micro-grid system. If there is a non-isolated inverter within the system, it would become a concern whether or not the DC source to that inverter is grounded. With the AC-link integrated isolation, the non-isolated inverter can be connected to the system, and the AC-link converters will adapt to its floating neutral without any considerations necessary.

Leverages Motor Drive Technologies (includes a variable speed drive (VSD)): The DRI leverages industrial variable speed drive technologies, and can therefore take advantage of advances in the design, manufacturing process, and supply chains for industrial VSDs. In fact, the DRI's microgrid port is based on a VSD design and has the capability to operate variable speed motor loads. This is a legacy of advanced military motor drives developed by Princeton Power Systems' [3] technology that continues to cross-pollinate our inverter products such as the DRI. Further leveraging cross-pollination with industrial motor drive technology is crucial to meeting a $1/W installed cost for PV and $0.10/W cost for power electronics specifically.

The SEGIS program was an approximately three-year, three-stage effort (approximately one year per Stage). It emphasizes the development of advanced inverters/ controllers, and other balance-of-system components for photovoltaic (PV) distributed power applications. SEGIS products developed under this program may be compatible with any of the three primary PV market segments that are connected to utility distribution systems: residential (less than 10kW, single-phase), small commercial (10 to 100kW, typically three-phase), or commercial (greater than 1000kW, three-phase). The DRI is a 100kW three-phase commercial product. Advanced integrated inverters/controllers may incorporate energy management functions and/or may communicate with compatible stand-alone energy management systems and with utility energy portals (such as smart metering systems). Communications are a critical and integral function to be included with PV system inverters, controllers, and balance-of-system hardware as the utility grid becomes reconfigured toward a more distributed-generation grid. Innovative grid integration through communications technologies and a multiplicity of interface options, such as working with other distributed generation systems in a micro-grid, expands installation opportunities.

Beyond Stage 3, PPS has partnered with Public Service Electric and Gas (PSE&G) to propose a **SEGIS AC** innovative project that supports high penetration of PV. PSE&G, the largest electric utility company in New Jersey, has some of the highest penetration rates of solar in the country, and is at the forefront of planning for significant additions of solar and wind, while PPS is a leading developer of advanced electronics systems, storage systems, and manufacturing systems in Princeton, NJ. As PV technologies become more ubiquitous, these systems may impact grid reliability on both the distribution systems and transmission systems (e.g., higher magnitude and more frequent voltage fluctuations).

This negative impact on grid reliability may cause utilities to severely limit PV installations or severely increase integration and interconnection costs. Our team will demonstrate the Demand Response Inverter (DRI) with integrated energy storage and grid support controls in areas with high penetration of solar energy that is disrupting the grid. The DRI developed under the SEGIS program is a four-port inverter that has two DC inputs, and is designed to support the high penetration of renewable energy sources by levelizing solar output so that it is in line with electrical demand. The development effort for the **SEGIS AC** program will be focused on sizing the storage component for the specific demonstration sites, integrating communications with the PSE&G operators, demonstrating functions, and analyzing results and economics. The DRI combines the functionality of both PV and battery inverters into one integrated system that reduces the levelized cost of energy.

This final report provides details of project status and progress made since inception of Stage 3, and provides an overview of all three stages, progress on commercialization, and successes and lessons learned. The report is divided into following sections: Section 3 describes the project overview. Section 4 reports project status, overall and by task. Section 5 describes the latest product design and specifications. Section 6 describes Assembly and Test Facility upgrades. Section 7 describes the progress on test plans, including compliance, reliability, and beta testing. Section 8 covers details on marketing launch and beta test plans. Section 9 documents the perceived impacts on the future of utility, customer, and PV applications. The last section (10) provides a summary of the project.

3. SEGIS PROJECT OVERVIEW

The PPS 100kW Demand Response Inverter (DRI) is a unique and innovative four-port power inverter that is poised to become an integral part of the smart grid supporting distributed generation and demand response applications. The DRI is also capable of becoming the key component in micro-grid applications, allowing for multiple energy sources that can be stored and distributed to critical loads reliably.

Some of the changes and opportunities in the electricity market that are evolving now and precipitating the transition to advanced systems requiring DRI technology include:

Solar Backup Power: With the DRI, it is possible to integrate PV arrays with on-site generators, allowing the array to continue operating when the grid goes down; saving fuel, money, and increasing positive perception of solar systems.

Demand Response/Dispatch: Trimming loads during the grid's peak usage times provides clear benefits to the electric grid, and can provide economic benefits to the user. By utilizing the DRI's five smart relays, non-critical loads can be shut off at peak times, or heating and cooling loads can be shifted earlier or later to minimize energy consumption during certain times of day. Load curtailment does not have to be simply "on or off."

Energy Storage Integration: Integrating the DRI with the solar array and energy storage provides a broad range of additional possibilities. The solar resource can be viewed by the grid operator as predictable and reliable, responding to price signals and time-of-use needs, and providing grid support functions in real-time. When multiple loads, storage, and generation sources are managed effectively through a DRI, the value, reliability, and security of the energy system are maximized. All available resources are utilized to their maximum efficiency and effectiveness, based on the price signals and environmental signals available.

Regulatory Services: Area frequency regulation, VAR support, and other services are increasingly being embraced by grid regulators such as the Pennsylvania, New Jersey, and Maryland (PJM) Interconnection. Solar resources can provide their full value as a capacity resource when combined with load control or energy storage through the DRI.

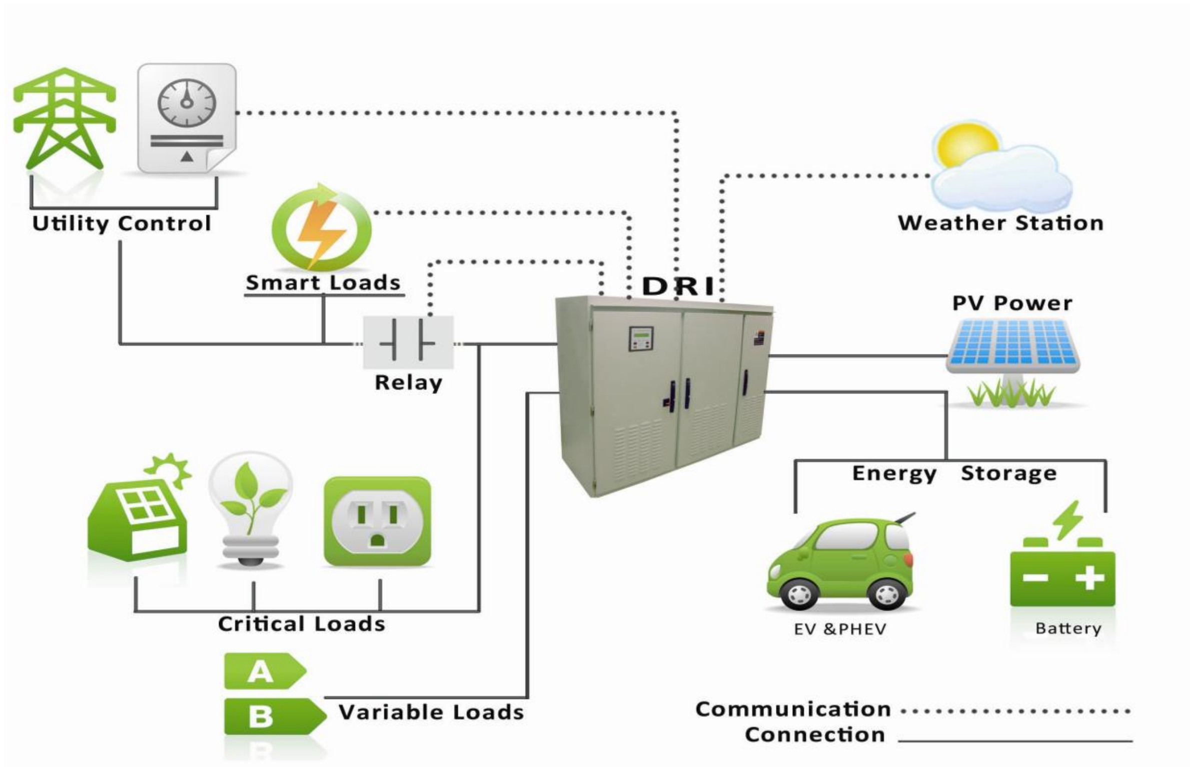

Figure 1:100kW DRI Concept

3.1. Objectives

SEGIS products developed under this program may be compatible with any of the three primary PV markets segments that are connected to utility distribution systems—residential (less than 10kW, single-phase), small commercial (10 to 100kW, typically three-phase), or commercial (greater than 100kW, three-phase). Advanced integrated inverters/controllers may incorporate energy management functions and/or may communicate with compatible stand-alone energy management systems and with utility energy portals (such as smart metering systems). Communications are a critical and integral function to be included with PV system inverters, controllers, and balance-of-system hardware as the utility grid becomes reconfigured toward a more distributed-generation grid. Innovative grid integration through communications technologies and a multiplicity of interface options, such as working with other distributed generation in a micro-grid, will be part of the grid of the future.

3.2. Scope

The SEGIS program was an approximately three-year, three-stage effort (approximately one-year per stage). It emphasizes the development of advanced inverters / controllers, and other balance-of-system components for photovoltaic (PV) distributed power applications. In Stage 1, the concept and design, feasibility, and cost-effectiveness of the Demand Response Inverter was analyzed and shown. In Stage 2, PPS successfully developed and tested the 100kW DRI prototypes. In Stage 3, PPS aggressively pursued the opportunity to commercialize its advanced inverter technology through transitioning the technology from a prototype to a production-ready design and pilot production run. This stage cumulated in late September with a Site Demonstration Conference at the PPS 200kW solar field that showcased the DRI's unique capabilities.

3.3. Methodology

3.3.1. Stage 1

During this stage, PPS developed a sophisticated reliability model for the components, subassemblies, and complete inverter, and used it along with the Solar Advisor Model (SAM) [4] for measuring Levelized Cost of Energy (LCOE) to make the inverter perform optimally under the SEGIS evaluation criteria. The power electronics and mechanical packaging designs were completed. Significant progress was made on developing the inverter's control system, and the strategy for implementing external communication was defined.

The completion of the detailed inverter design allowed PPS to confirm final inverter cost and efficiency estimates with detailed calculations. Remaining risks to the inverter development were identified, and mitigation strategies were defined for eliminating them early in Stage 2.

Continuing work, both on developing the advanced control system for the inverter and on high-frequency power electronics testing, was shared with other programs supported by the DOE, the Navy, and the Army. This work translated directly into furthering the technology required for the commercial DRI.

In Stage 1, PPS identified customer installation sites and evaluation sites for Stages 2 and 3. PPS established relationships with key solar integrators to help bring the DRI to market in Stage 3.

3.3.2. Stage 2

In Stage 2, PPS progressed through developing the prototype DRI. Two units were assembled and tested for performance and functionality. Witness testing of the first prototype took place in May 2010. The following features and functionalities were confirmed:

- Multi-port operation and power management.
- Multiple modes of operation—demand response, distributed generation, VAR source/PFC, and emergency/standalone mode.
- Photovoltaic (PV) Maximum Power Point Tracking (MPPT) function
- Battery 3 step charging and discharging
- Load shedding and Motor Variable Speed Drive
- IEC 61850 [5] compliant remote control and monitoring

Other Design features of the DRI incorporated in Stage 2 were:

- Improved reliability—longer MTBF, longer life
- Improved inverter performance—efficiency, power quality, system response
- Lower product cost—modularity, COTS component, commonality of stages

- Improved BOS cost—integration of BOS components
- Lower LCOE

In Stage 2, the SEGIS DRI project opened new business opportunities for PPS that facilitate commercialization of the DRI technology.

3.3.3. Stage 3

In Stage 3, PPS aggressively pursued the opportunity to commercialize the DRI advanced inverter technology. The inverter was field tested in various unique environments and applications to evaluate and demonstrate the reliability and cost-effectiveness of the system. PPS beta tested the DRI in 2011 and will get commercial certification and make the DRI available commercially for sale by end of 2011.

PPS has progressed on the commercialization of the DRI since the prototype development in Stage 2, which was completed in June 2010. The design for manufacturability, reliability, acoustics, and cost of the production units was finalized and parts procured from key suppliers. Cost targets were established based on market-driven production requirements. Supplier and cost-of-goods analysis was performed. Assembly and test facilities were upgraded for the pilot production run. Test plans were developed for certification, environmental, life cycle, and demonstration testing. Marketing launch efforts are still underway. Strategic partnerships were built with utilities, power solution providers, and users such as cities and educational institutes. The plan for beta testing was developed.

The pilot production run is ongoing with seven units slated for completion. In late September 2011, the site demonstration conference was hosted at PPS's 200kW solar field in Princeton, NJ, to demonstrate the unique features of the DRI using pilot unit DRIs.

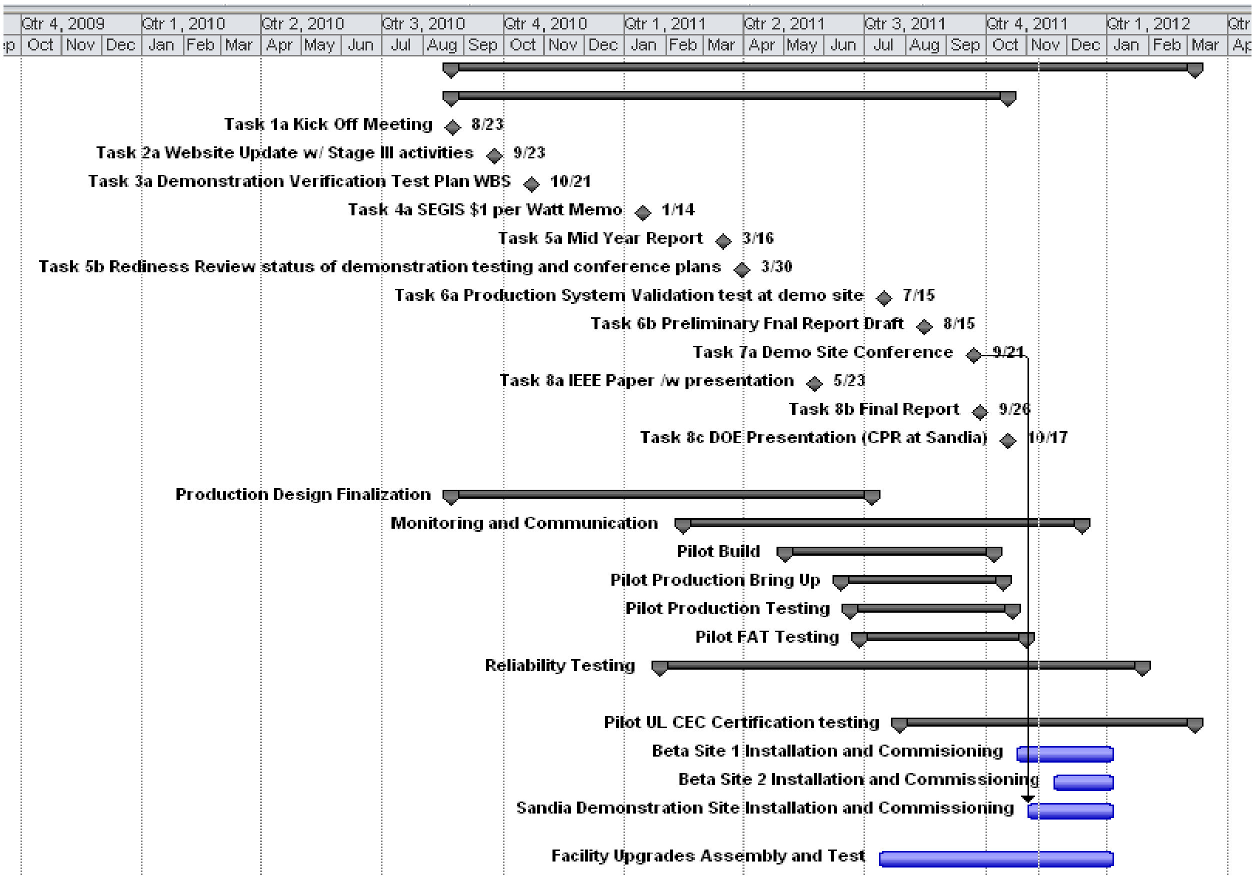

Figure 2: SEGIS Stage 3 Schedule

4. PROJECT STATUS, TASK DESCRIPTIONS, GOALS AND RESULT

4.1. SEGIS Stage 3 Contract Deliverable Tasks

Tasks	Description	Due Date
1	a. Stage 3: Kickoff Meeting Status Presentation via web conference or at contractor facility as directed by SDR	August 23, 2010
	b. Stage 3: Work Plan including Work Breakdown Schedule with responsibility matrix	Due at Kickoff Meeting
2	a. Website update with Stage 3 activities	September 23, 2010
3	a. Demonstration Verification Test Plan including a WBS of test schedule	October 21, 2010
4	a. Sandia Energy Plan Memo ($1 per Watt Memo) **(As directed by SDR)**	January 14, 2011
5	a. Stage 3: Mid-Year Report **(As directed by SDR)**	2 weeks prior to assigned web conference or site visit
	b. Demonstration Readiness Review via web conference or at contractor facility. **(As directed by SDR)**	March 23, 2011 – April1, 2011
6	a. Production System Validation Test at contractor facility or at demonstration site **(As directed by SDR)**	June 27, 2011 - July 11, 2011
	b. Stage 3: Preliminary Final Report draft **(As directed by SDR)**	August 15, 2011
7	a. Demo Site Conference **(As directed by SDR)**	September 28, 2011
8	a. Stage 3: Paper with presentation **(As directed by SDR)**	During Stage 3 as directed by the SDR
	b. Stage 3: Final Report **(As directed by SDR)**	September 26, 2011
	c. Stage 3: DOE presentation @SPI 2011 **(As directed by SDR)**	October 17, 2011

4.1.1. Task 1: Kick-off Meeting

The SEGIS Stage 3 kick-off meeting was held on August 23, 2010, at the PPS facility in Princeton, NJ. The project goals and work plan were presented and reviewed. An action item list was generated for the Stage 3 program. This deliverable was completed in August 2011.

4.1.2. Task 2: Website Update with Stage 3 Activities

This task entailed updating the PPS and Sandia Web sites with pertinent and up to date SEGIS Stage 3 activities, updates and DRI Specifications. This deliverable was completed in January 2011.

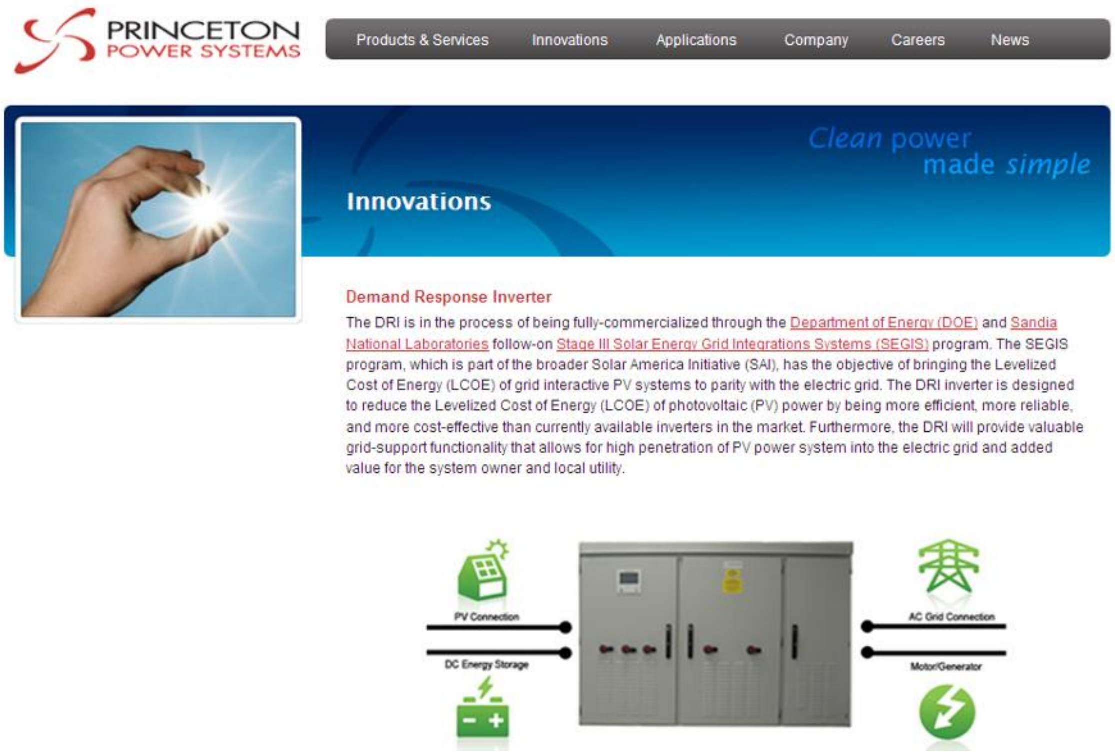

Figure 3: PPS DRI Webpage

4.1.3. Task 3: Demonstration Verification Test Plan

This deliverable provides details of the test plan to validate production units for the quality and workmanship applied, as well as the ability of units to perform in the field as intended. The factory acceptance test plan (FAT) is in accordance with the UL 1741 [6] standard. The test plan includes a list of tests to be performed along with the test schematic, test procedures, and test results documentation. The plan also covers the FAT certification to be attached to each unit shipped.

The Demonstration Verification Test Plan also provides details of the test plan for the Demonstration Site Conference planned for September 2011. The objective of the Demonstration Site Conference was to demonstrate functioning of the DRI in real-life situations, i.e., installed outdoors and interfaced with solar field, battery bank, grid, and local loads. The unit was operated locally as well as remotely via an Ethernet based communications link. The unit was operated in various operating modes and provided operating data on local Human Machine Interface (HMI) and Remote Supervisory Control and Data Acquisition (SCADA) stations. This task was completed in October 2010.

4.1.4. Task 4: Sandia $1 per Watt Energy Plan Memo

This deliverable was a report that addressed the DOE $1/W targets for PV systems by addressing the 5 items below:

1) How does your SEGIS development help the nation meet the $1/W target for photovoltaic systems?
   Answer SEGIS advances and technical innovations enable developing infrastructure to produce enabling technologies, building the workforce to support demand, enablement of the grid of the future through "smart grid" technology imbedded in products, and development of supply chains to support this technology.

2) In what timeframe do you anticipate that your technology advancement will impact costs such that the $1/W PV systems can be realized?
   Answer PPS believes that the product will be optimized by 2016-2017, and increased sales demand will enable us to meet this goal.

3) How will your technical innovations help meet both domestic and international goals equivalent to $1/W?
   Answer The cost of the DRI can be reduced by reducing the size of the power electronics through technical innovations such as the central resonant link, combined with higher switching frequencies. The ability of the system to make the most effective use of solar energy will be achieved by developing flexible energy storage options to help meet the $1/W goal.

4) Does your new development(s) require additional investigations or research? (Please estimate to what extent)
   Answer At this time the Central Resonant Link needs additional development before it can be released to production. PPS anticipates ongoing development over the next two years. Other technologies, such as silicon carbide switches, have the potential to dramatically decrease the size and cost of the power electronics in the future. PPS has ongoing technical development programs with the DOE and the Navy.

5) Does your current development meet reliability goals and Levelized Cost of Energy as set forth in the original proposal?
   Answer As originally proposed, the goal for the LCOE for the 100kW DRI was 23.21 cents/kWh for a complete 100kW PV installed system. The latest calculation of LCOE using SAM 2010 [4] for the first run of 100kW DRIs is 11.0 cents/kWh. Taking into account all of the above efforts to reduce cost in line with the goal of $1/watt, the LCOE can be further reduced from the present estimate of 11.0 cents/kWh.

This task was completed in January of 2011.

4.1.5. Task 5: Mid-year Report and Demonstration Readiness Review

The mid-year report was an update on project progress to the mid-year report timeframe. It also addressed plans and schedule of the project going forward. The report was followed by an on-site visit from the Sandia team to review the contents of the report and witness actual project progress.

The DRI product design is on track to meet the desired goal of $1/watt PV system cost and LCOE cost target of $1/kWh. The PPS production facility has been expanded and preparing for initial production quantities of 60-70 units per year.

PPS remains confident that the DRI controller is a promising technology that can provide commercially viable interface for PV system integration into Utility Grid. The controls and communication features allow the units to actively communicate with other units and with energy management system to work in a distributed-generation grid. The DRI will increase market acceptance of PV by further incentivizing end users to consider solar array installations. It will provide an improved economic payback based on lowered LCOE, and will also provide additional economic incentives that a traditional solar array does not. For some customers, the critical functionality of energy management and load control are the primary reasons the array is attractive. Furthermore, the DRI technology will assist utilities and grid operators with solving the issues of high-penetration PV integration and their own peak-power requirements.

The SEGIS DRI project has also opened many new opportunities for PPS to develop systems similar to DRI for other applications thereby helping the growth of PPS and the growth of green energy.

This task was completed in April 2011.

4.1.6. Task 6: Production System Validation Test and Draft Final Report

The Production System Validation Test was completed in late June 2011. A team from Sandia visited PPS and reviewed project status and the site demonstration conference plans at PPS scheduled for September 28, 2011. A draft final report was written and submitted on August 23, 2011.

4.1.7. Task 7: Demo Site Conference (an Island in the Sun)

A Demo Site Conference was held on September 28, 2011. This conference was held at PPS's 200kW solar field at 201 Washington Road in Princeton, NJ. The intent of this Stage 3 demonstration conference was to show utilities, customers, stakeholders, and government officials the DRI functionalities that make it attractive. This includes grid interactivity; new hardware capabilities, including four-port operation, remote monitoring and communication, load shedding, and other innovative application options and value-added features. The impacts of DRI advancements were presented with use case scenarios presented in relation to the distributed generation problems utilities and stakeholders need to be solving now or in the near future. This conference was also a public demonstration of progress, success, lessons learned, barriers overcome, and future needs as standards and codes catch up to SEGIS advances. The goals of the Demo Site Conference were technical, educational, and market outreach.

4.1.8. Task 8: White Paper and Presentation, Final Report, Public / DOE Presentation

The final task in Stage 3 is twofold: a white paper and presentation. The Final report is to be written and was due September 26, 2011, and the DOE presentation took place on October 17 at Solar Power International 2011 in Dallas, TX.

4.2. Overall Project Status

The DRI program is now in the pilot build stage. Five pilot units are in various states of completion.

Operational testing is underway. PPS will do some initial pre-UL compliance testing to verify that key aspects of the design are within boundary conditions of compliance, as well as some internal beta testing utilizing a 200kW Solar Farm that was installed at Princeton Power System's Washington Road facility in August and September of 2011.

4.3. Production Design Finalization

In Stage 3, updates to the DRI were made to the design based on test results, feedback from Sandia, build notes, and cost reduction efforts. The DRI was repackaged mechanically and the next generation controls were implemented. Numerous software features were completed and enhanced. The remote communications and monitoring features were integrated into the new door mounted HMI feature. The design was completed and design documentation has been updated.

4.4. Procurement

Procurement for the seven pilot units has been ongoing since September 2010 and is complete. Construction of a 200kW solar field and two 100kWh battery backup modules has been completed.

4.5. Facilities Upgrades for Assembly and Test

4.5.1. Production Facilities

A number of changes have occurred over the Stage 3 program. Initial production of the DRI was begun at PPS's new production facility located at 3490 U.S. Route 1 in Princeton, NJ. PPS began its facility expansion in January. In February 2011 PPS suffered a serious fire at the 201 Washington Road facility. Because of this, the company had to consolidate operations at the 3490 facility. In May PPS learned that we would not be able to return to the 201 Washington Road facility. The 3490 facility was originally not intended to house the entire company and was not large enough to accommodate the entire company. PPS then leased a 10,000 square foot facility large enough to house the company under one roof. PPS began moving production to this facility in June of 2011. PPS anticipates that by March 2012 the company will be consolidated at 3175 Princeton Pike Lawrenceville, NJ.

4.5.2. Manufacturing and Test Facilities Plan

The DRI pilot run is being assembled and tested at both the 3490 U.S. 1 location and the 3175 Princeton Pike facility. There are designated DRI assembly and test areas in both facilities.

4.6. Pilot Production Plan

4.6.1. Build Seven Pilot DRI 100kW DRIs

PPS is building seven Pilot production 100kW DRIs during Stage 3. It is anticipated that three units will be used at various beta sites, one unit will be used for compliance testing, one unit will be used for reliability testing, and two units will be built as back-up units. The pilot run is underway. The first three units are completed and the next two are 75% completed.

4.6.2. Assembly of Units

The initial target production volume for this product is seven units in the fourth quarter of 2011 if the market will allow. This initial production volume allows for a broader-scale field testing of the product with a limited number of units in the field in the first year before ramping up production to meet further demand.

4.6.3. Documentation

The inverter user manual will be completed before the Demonstration Site Conference. The operational features of the inverter are defined. The user manual will describe system specifications and capacities, important safety information, installation requirements and procedures, system setup and configuration instructions, and descriptions and instructions for using all of the inverters features. This documentation will be based on the existing user manual for PPS's 100kW inverter.

System manufacturing documentation has been developed and finalized during the building stage of the pilot units. The manufacturing documentation will include a "Build Book" which illustrates exactly how to assemble each unit from start to finish, a system wiring diagram, a system labeling diagram, and a detailed bill of materials.

4.7. Test Plan

Testing and verifying the product design is done according to a testing program that has been developed by PPS and according to best practices from the military power electronics industry, commercial power electronics industry, and internal team experience in UL compliance testing. The steps to validate performance, safety, and functionality include:

1. Integration and Bring-up Design Verification Testing (DVT)
2. Functional Testing Pre-Factory Acceptance Testing
3. Factory Acceptance Testing (FAT)
4. Compliance Testing: Underwriter's Laboratories testing and certification (UL)

5. Reliability Testing
6. Beta Testing

4.7.1. Test Planning

The planning process for DVT, Pre-FAT, FAT, and UL certification testing will leverage the existing test plans that were used for testing the PPS 100kW inverter, which occurred during Stage 1 and DRI specific test plans that have been developed in Stage 2.

4.7.2. Design Verification Testing

DVT occurs at the component, subassembly, and full-system levels. This testing is currently underway and is described further in the test Section 7 of this report.

4.7.3. Functional Testing

Functional or Pre-FAT testing verifies functional performance of the system, including efficiency, power quality, software functions, and basic and advanced functionality. Testing will also include MPPT, verification of setpoints, islanding, and other pre-UL safety related tests. Test details and current schedule is described in the test Section 7 of this report.

4.7.4. Factory Acceptance Testing

FAT occurs after pre-FAT, and consists of a subset of the pre-FAT tests. FAT is closely aligned with the production tests that will be run on each unit in production. It is expected that the pilot units will successfully pass FAT with minor or no issues. Test details and current schedule is described in the Section 7 of this report.

4.7.5. Compliance Testing

UL compliance testing will occur following successful factory acceptance testing of the pilot units. Test details and the schedule are described in the test Section 7 of this report.

4.7.6. Reliability Testing

Reliability testing ensures that any likely failure points and weak design points that have not already been uncovered are exposed. Testing is done on the full system, with extended 24-hour burn-in at elevated temperature and voltages, in order to stress components to levels they would normally not experience in normal operation. Test details and current schedule are described in the Section 7 of this report.

4.7.7. Beta Testing

Beta Testing will occur in parallel with UL and long-term endurance testing – and is described further in Section 7.

5. DRI PRODUCT DESIGN AND SPECIFICATIONS

In order to meet the objectives of the SEGIS program and our product development, PPS has successfully demonstrated a very technically ambitious concept. The DRI concept was broken into three major categories:

1) Design a flexible hardware platform based on new circuit topology and components
2) Design control software to provide four-port operation and value-added functions
3) Adhere to best practices of commercial solar inverters and electronics

The software and controls operates using a single control board, which runs all four ports simultaneously and also provides application-level programming capability. The hardware platform has also been designed to meet NEMA 3R ratings for outdoor operation, high-temperature environments, UL regulations, and all electrical operations required for grid-tied generation systems. Finally, a flexible communications system has been designed to allow integration with advanced communications protocols.

The design has been reviewed for reliability and audible acoustics by independent consultants and refined for manufacturability. The following sections provide details of the final DRI product design.

5.1. Cabinet Outline

As shown in Figure 4 , the Demand Response Inverter (DRI) cabinet is designed for outdoor installation and is NEMA 3R Rated. The cabinet has lifting, moving, and anchoring provisions for installation on a concrete pad. Power cable entries and exits are in the floor of the unit. A cabinet grounding stud is provided at the bottom on both sides. Disconnect switches are integrated into the cabinet to minimize BOS cost and space. Local operator controls, i.e., the Human Machine Interface (HMI), are mounted on the front door of the cabinet. A local Ethernet interface is also provided with the HMI assembly. A safety cover with lockable swing-out door is installed to protect the HMI against unauthorized use. The safety cover will also protect the HMI touch screen from harmful UV radiation.

5.2. DRI Internal Layout

Figure 5 shows the internal arrangement of 100kW four-port DRI. The layout is modular. The components are placed such that they are easy to install, replace, test, and trouble-shoot. Sub-assemblies are easy to handle by weight and size. All control sensors are mounted near the point of sensing while all transducers are mounted away from power components for electrical and EMI isolation. Each sub-assembly is grounded individually to the common ground bus provided internally.

Figure 4: 100KW Four-port DRI Cabinet

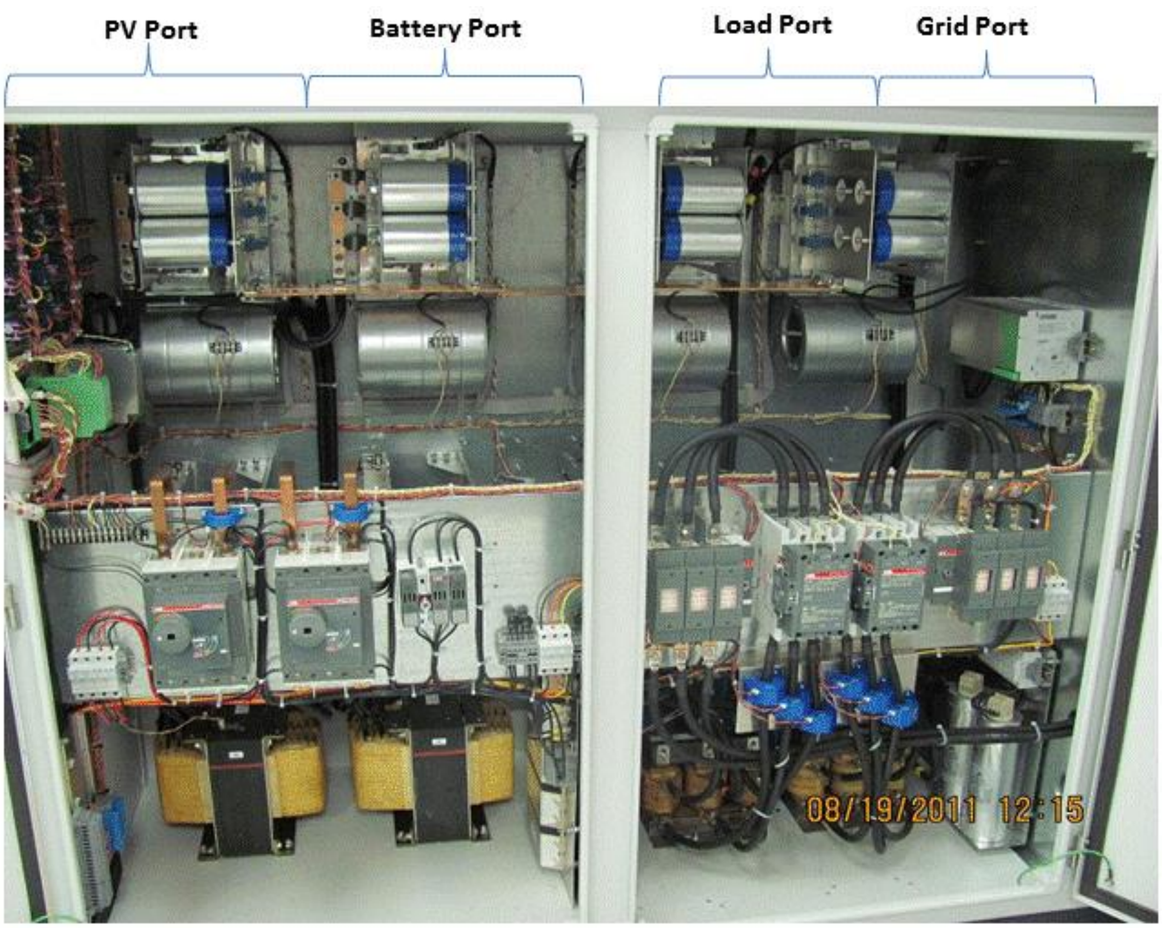

Figure 5: 100kW Four-port DRI Packaging Layout

5.3. Major Sub-components

The major sub-components of the DRI can be seen in following figures:

Figure 6: Door-mounted Human Machine Interface (HMI) allows operator to control the DRI and monitor its performance.
Figure 7: The location of the two DC ports, which are on the left side of the DRI.
Figure 8: The back side of the left hand door, where the HMI unit, communication interface, and controller card are housed in a NEMA 4 enclosure.
Figure 9: DC Port Disconnects mounted in the left side of the DRI, disconnect handles protrude through the left door.
Figure 10: AC Ports located behind the center door of the DRI.
Figure 11: Fuse and breaker protection located behind the center door of the DRI.
Figure 12: 60Hz Transformer located on the right side of the DRI.

Figure 6: Human Machine Interface (HMI)

Figure 7: PV and Battery Ports

Figure 8: HMI and DRI Control Boards

Figure 9: PV and Battery Disconnects

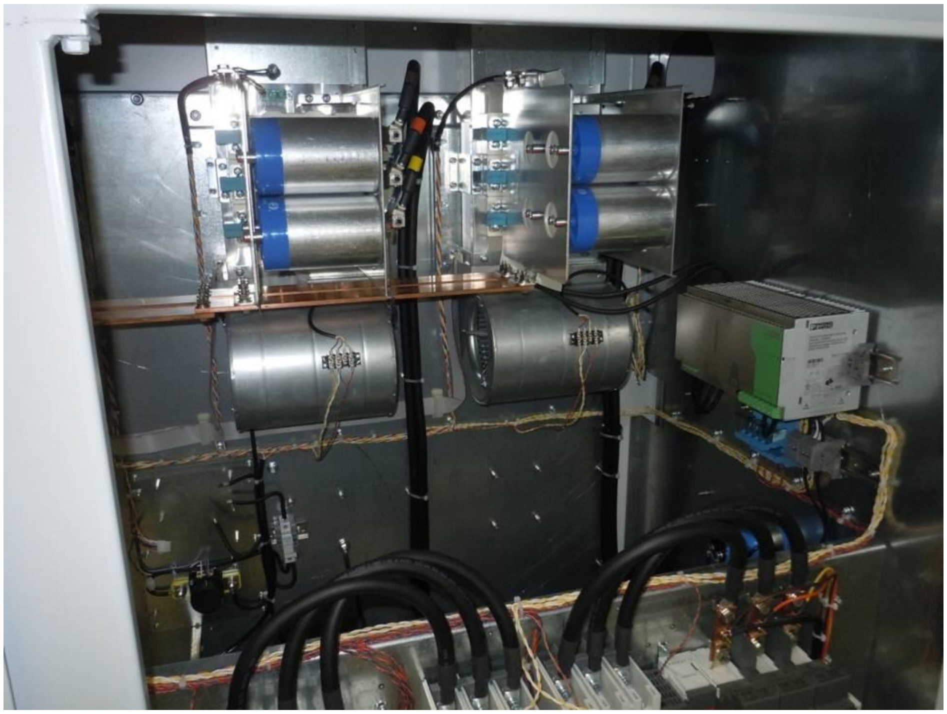

Figure 10: Load and Grid Port

Figure 11: Fuse and Breaker Protection

Figure 12: 60Hz Transformer

5.4. Monitoring and Communication System

During Stage 3, PPS enhanced the development of the remote-monitoring and communication system that is used for field monitoring. The peer-to -peer remote monitoring system was upgraded to a web-based user interface of the monitoring system that is used to access data generated by the inverters in each installation. The monitoring system is designed to capture a large amount of detailed data. Data recorded includes input and output voltages, input and output currents, power meter readings, and multiple temperature measurements, as well as some internal voltages, currents, and faults that may have occurred. This data allows the user to remotely monitor performance of the system and detect any behavior that may require attention.

5.4.1. Communication Overview

The DRI system uses a dedicated printed circuit board to implement all functionality related to communication and remote monitoring. The functional separation of communication hardware and inverter control hardware allows the communication system to adapt to changing user requirements while the inverter control board remains as unchanged as possible.
The communication board uses a serial link and a proprietary protocol for sending and receiving data to and from the control board. For communication with the outside world, a number of interfaces such as Ethernet, RS-485, or RS-232 are available and can be used for remote monitoring and control as well as for interfacing to any control infrastructure already present at the customer site. The communication board is also responsible for implementing specific SCADA protocols.

5.4.2. Communication Infrastructure Overview

The communication hardware components inside the DRI unit and the server infrastructure for the remote monitoring were changed in Stage 3. Figure 13 shows an overview of the monitoring and communication infrastructure. The components are described further in the following sections.

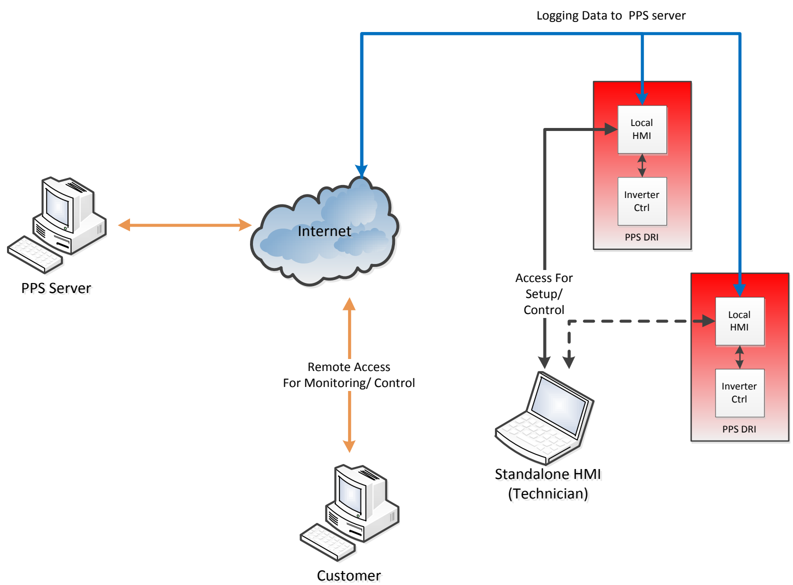

Figure 13: Monitoring and Control Infrastructure

5.4.2.1. Local HMI

The DRI uses a single board computer (SBC) for communication. It is also used for implementing the Human Machine Interface (HMI) and for direct user access to the unit. The control interface is implemented using an LCD display with touchscreen interface. Figure 14 shows the selected single board computer (SBC) together with the LCD screen.

Figure 14: Selected SBC, Shown with LCD Touchscreen

5.4.2.2. Standalone HMI

For standalone monitoring—for instance by a technician during the installation or test of a unit—the communication board provides a web-based control interface. The technician connects to the DRI unit through an Ethernet jack provided on the front of the unit as part of the local HMI panel shown in Figure 15, thereby gaining full access to all internal control parameters.

Figure 15: Picture of Installed Local HMI Front Panel

5.4.2.3. Remote HMI

For remote monitoring and control, a centralized server is used. The server monitors all, or at least a large number of, PPS units which send logging data to the server at regular intervals. Customers can log into the server to see the status of the DRI they own and have access to. The display interface that is displayed when using remote access closely resembles the one used when using the standalone HMI.

The remote HMI offers the review of historical performance data, using the stored logging data. The user can also view real-time data of a particular unit. For this function, the unit in question sends raw data to the server, which processes it into viewable plots, thereby reducing the processing load on the communication board inside the unit.

5.4.3. Local HMI & Unit Control

Figure 15 shows a picture of the Local HMI installed in a DRI unit. The figure shows the touchscreen and under it a key switch (for restricting access to local or remote), the Stop/Reset button, and an Ethernet port that is wired to the front of the unit to provide easy access for technician laptops. All local control is done though the touch-screen. Figure 16 through Figure 18 show some control screens for main control functionality.

Access to the unit is organized in three different levels ranging from monitoring only (basic) to full read and write permissions for all parameters (technician), with each of the levels having a different passcode (which is configurable). Figure 16 shows a screen capture of the initial login screen.

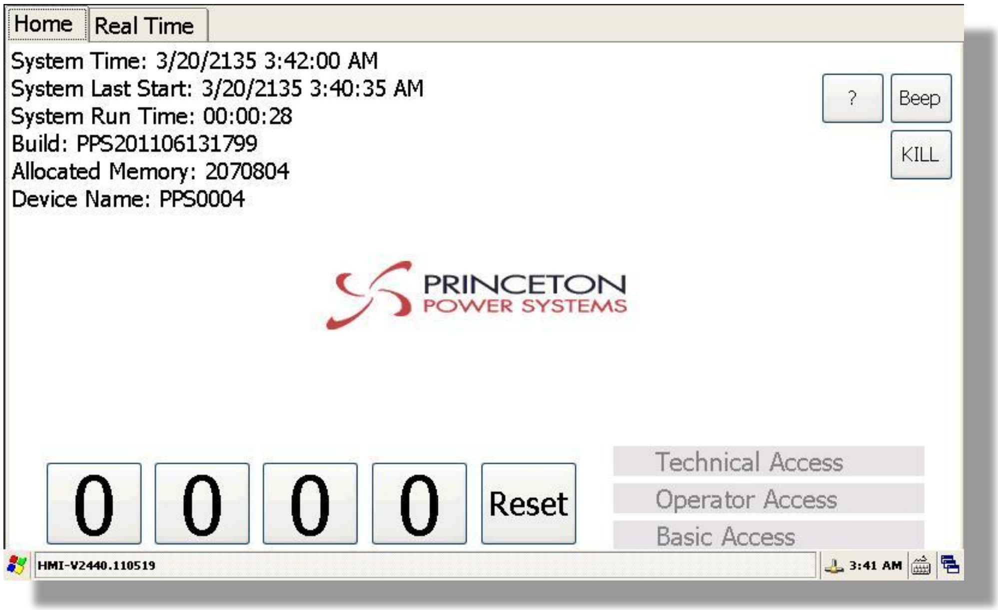

Figure 16: Password-protected Login Screen

The main screen shown to the user most of the time is the home screen, shown in Figure 17. The screen shows a status overview for each of the four DRI ports (PV, Battery, Grid, Load), as well as an inverter status in the center of the screen. Pressing each of the individual port status blocks changes the view to a screen with more details.

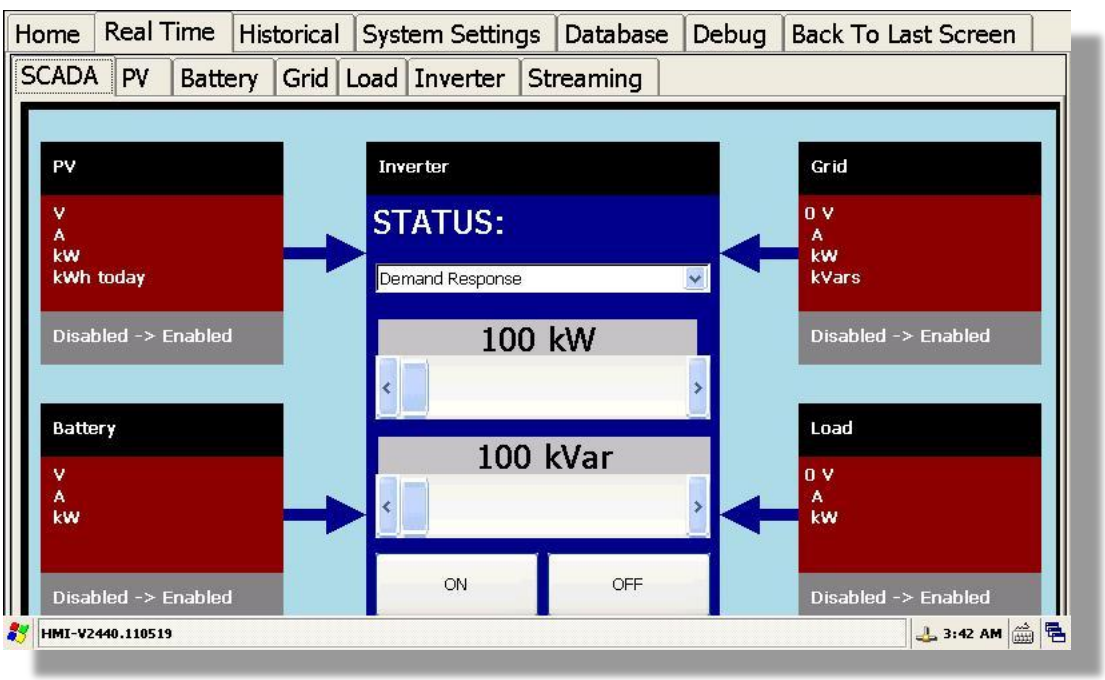

Figure 17: Main Inverter Overview Screen (Home) of Local HMI

The main inverter status has On/Off buttons as well as controls for selecting operating modes of the unit and specifying important operating parameters, for instance using sliders to set the output power level as shown in Figure 17.

Besides showing the momentary real-time status of the DRI, the Local HMI stores a limited amount of logged performance data, which can be viewed as well as analyzed. Figure 18 shows the screen used to select the date range of the data and parameters of interest.

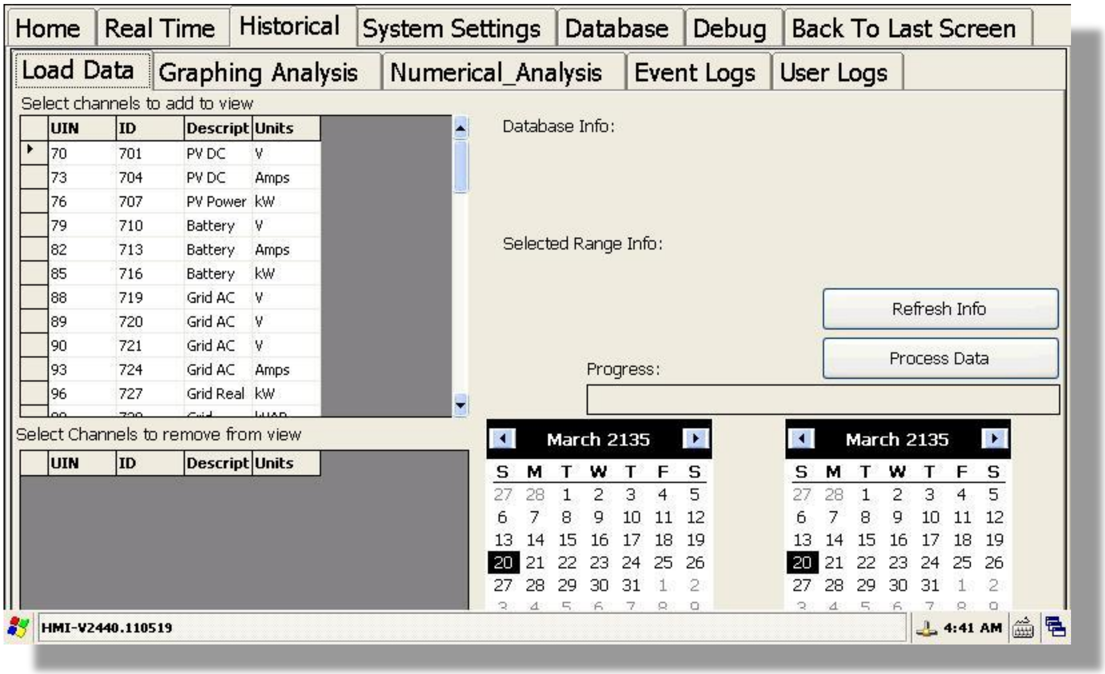

Figure 18: Data and Date Selection Screen for Local Data Analysis

5.4.4. Standalone HMI

Standalone HMI is a web-server-based interface, implemented using Flash for easy access. The Standalone HMI offers the same functionality as the local HMI when the unit needs to be operated locally for longer periods of time, such as when testing or commissioning, or when viewing the front of the unit is not possible. The interface mimics the look and feel of the Local HMI to offer the same user experience.

In addition, the Standalone HMI can be used as a remote server replacement in applications where access through the Internet is intermittent or non-existing.

5.4.5. Remote HMI

The remote Human Machine Interface (HMI) is implemented using a server. The server connects to all installed PPS units via the Internet using TCP/IP, either through Ethernet or another physical layer such as Wi-Fi or GPRS.

The server continuously receives status updates from all connected inverters and stores the data in an SQL database (Master Inverter Database). Users, i.e., owners of PPS inverters, connect to the server through the Internet as well.

Once their credentials have been established successfully, users can access historical as well as real-time operating data for the units they have access to. It is also possible to control those units remotely through the server. Figure 19 shows a diagram of the overall architecture of the remote HMI.

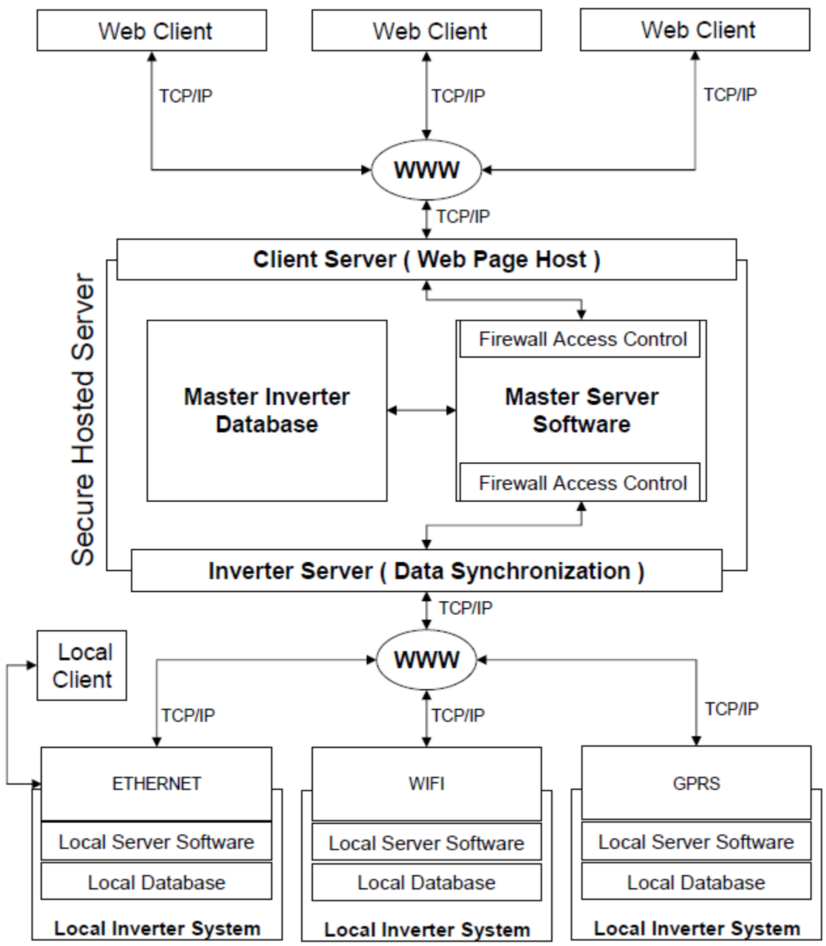

Figure 19: Internet Connectivity for Remote Monitoring and Control Server

5.5. Central Resonant Link

In Stage 1 of the program, PPS proposed using a novel Central Resonant Link (CRL) concept in which a central capacitor bank and a high frequency transformer take the place of a standard 60Hz transformer, which would be more standard technology. This CRL would be much smaller, lighter, more efficient, and cost effective.

5.5.1. Central Capacitor

Description
The central capacitor is the critical component of the central resonant circuit of the inverter. The central capacitor is first charged in one polarity and then reversed, transferring packets of energy from the input to the output of the converter. The central capacitor was identified as a high-risk item and was a key focus of the early development effort, which focused on the cooling requirements and hot spot challenges associated with high dissipation factor loss concentrations.

Stage 2 Final Design
The final central capacitor design comprises an array of small polypropylene film capacitors (Figure 20). While it would be more cost effective to use a small quantity of larger capacitor cans, the high dissipation factor requires a very large ratio of surface area to capacitor volume. The large number of small capacitors spreads the heat over a very large area, providing a large cooling surface and a very short thermal path length from the center of the capacitor to the outside air. This minimizes the thermal gradient inside the capacitor and reduces the temperature rise above ambient. Although assembly costs will be higher due to the high parts count, all parts are identical and can easily be wave soldered and are very suitable for efficient mass production. Since these capacitors are already produced by the millions, they are cost effective and competitive with the low volume, specialty larger film capacitors.

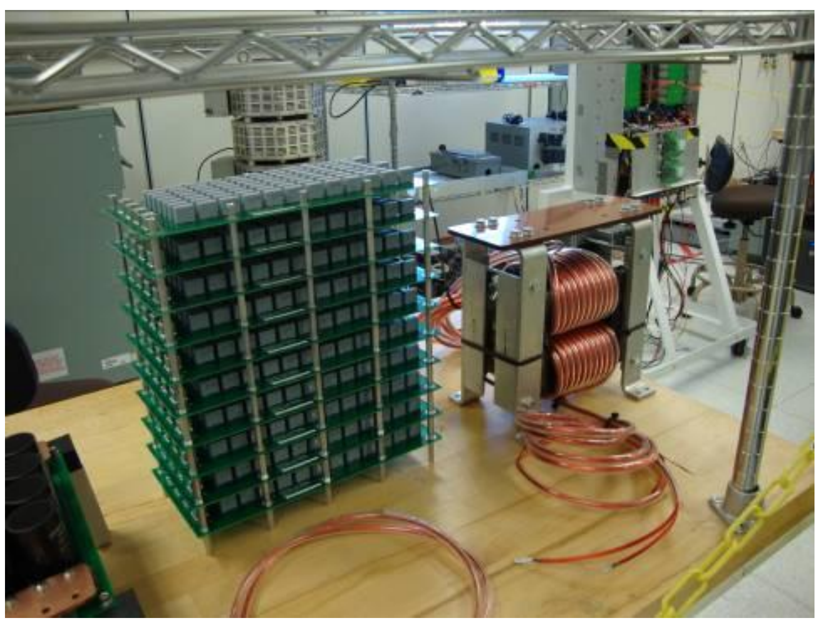

Figure 20: Prototype Central Capacitor Bank

5.5.2. Internal Transformer

5.5.2.1. Description
The internal high-frequency transformer transforms the internal resonant link voltage, minimizing current flow in the grid side of the inverter, and providing galvanic isolation between the solar array and output of the inverter. Due to the high frequency AC voltage, this

transformer is less expensive, more efficient, and smaller than a typical 60Hz transformer. The 50kHz transformer weighs about 20 pounds, as opposed to more than 1000 pounds for a 60Hz transformer.

5.5.2.2. Stage 2 Final Design

The internal transformer (Figure 21) has been designed for 50kHz operation. Nanocrystalline is the best choice for the core based on cost and efficiency. Although this is an expensive material per pound, the high efficiency and high performance require much less core mass than would be needed with conventional materials. Litz wire is wound on the core with a 1:1.75 turns ratio.

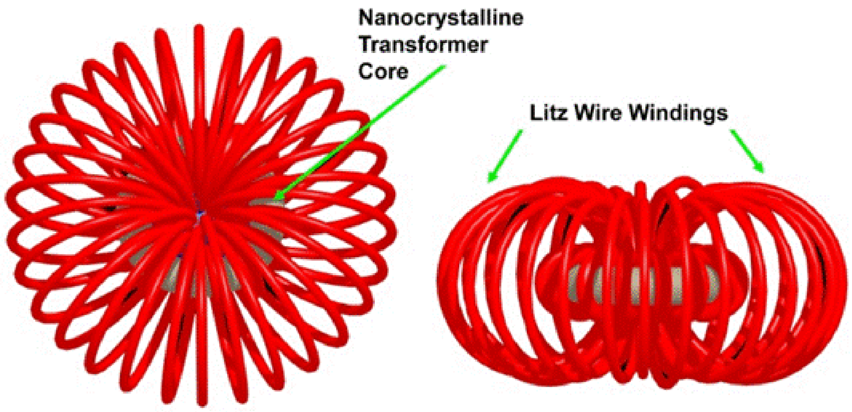

Figure 21: Internal Transformer - Air Cooled Version

The mechanical layout of the transformer involves several design considerations. Due to the high frequency magnetic field surrounding the transformer windings, the metal chassis must maintain an adequate clearance to prevent eddy current heating. To prevent a magnetic short circuit, no conductive path can be established through the center of the toroidal core, so mounting attachments must be installed around the perimeter of the core, or must be made of a non-conductive material. The current design for mounting and cooling the high frequency internal transformer is depicted in Figure 22. The litz wire windings are shown in red and blue.

The role of the CRL (central resonant link) is to transfer power between primary (DC side) and secondary (AC side) while keeping the central capacitor voltage around an optimized operating point (770V). Based on the voltage difference across this central capacitor, the CRL can operate in two different modes: normal and inversion. The operating mode of the CRL is not related to the DRI operation modes.

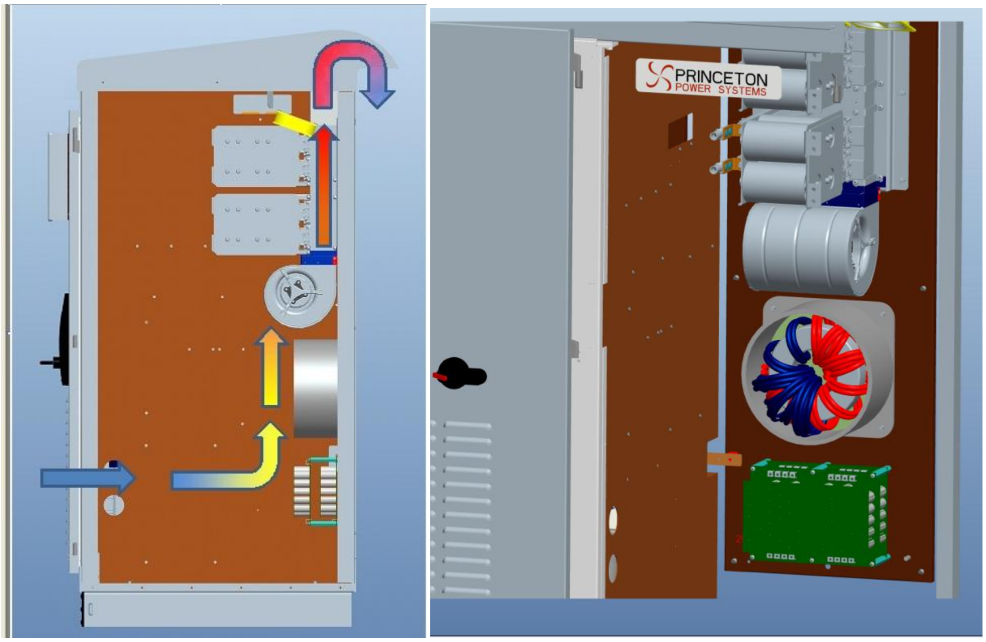

Figure 22: CRL Mounting and Airflow Design

When the voltage across the central capacitor is less than the optimized operating point (770V), the CRL operates in normal mode. During normal mode operation, switching in the CRL occurs with zero current (to minimize the switching loss), and the switching frequency is lower than the central bank's natural resonant LC frequency. When power flows from the secondary to primary side (example: grid charging the battery), the grid/local port side CRL bridge switches 50-50 and PV/battery side CRL bridge behaves as a rectifier (no switching occurs in this bridge and only diodes conduct). When the power flows from primary to secondary (e.g., PV to load port) the PV/battery side CRL bridge switches 50-50 and the grid/local port side CRL bridge behaves as a rectifier.

Inversion mode occurs when the central capacitor voltage exceeds its optimized operating point. This condition can occur due to transient loads such as motor braking. Inversion can be performed on either left or right hand side bridges and at the beginning or end of each pulse. The optimal method is a combination of inversion at the beginning of the pulse and frequency modulation. With the proposed method (combination of inversion and frequency modulation), only soft switching occurs, minimizing switching loss.

5.5.3. Central Resonant Link Risk Reduction Testing, 5kW@700VDC

In Stage 2, a bench-top CRL assembly was built and tested. Waveforms, test bed schematic, and test setups are shown in Figure 24 through Figure 25. Testing is described below and results are shown in Table 1.

5.5.3.1. Test Objective

- Demonstrate High Frequency Transformer operation up to 5kW @700VDC.
- Test Central Link Hardware for 20kHz DC/DC Operation up to 700VDC input

- Test Central Link Control Algorithms with Integrated v2.2 Control System

5.5.3.2. Test Procedure

- Setup test bed with 500Ω DC load on the dump load stack.
- Using a VARIAC, start testing from 10VAC to 480VAC (10VAC steps)
- Monitor and verify:
  a. Input capacitor voltage
  b. Output capacitor voltage
  c. Central capacitor voltage
  d. Switching frequency vs. resonance frequency

- Integrate central link control algorithms and monitor
  e. Input capacitor voltage prediction
  f. Output capacitor voltage prediction
  g. Central link capacitor voltage prediction
  h. Inversion time calculation

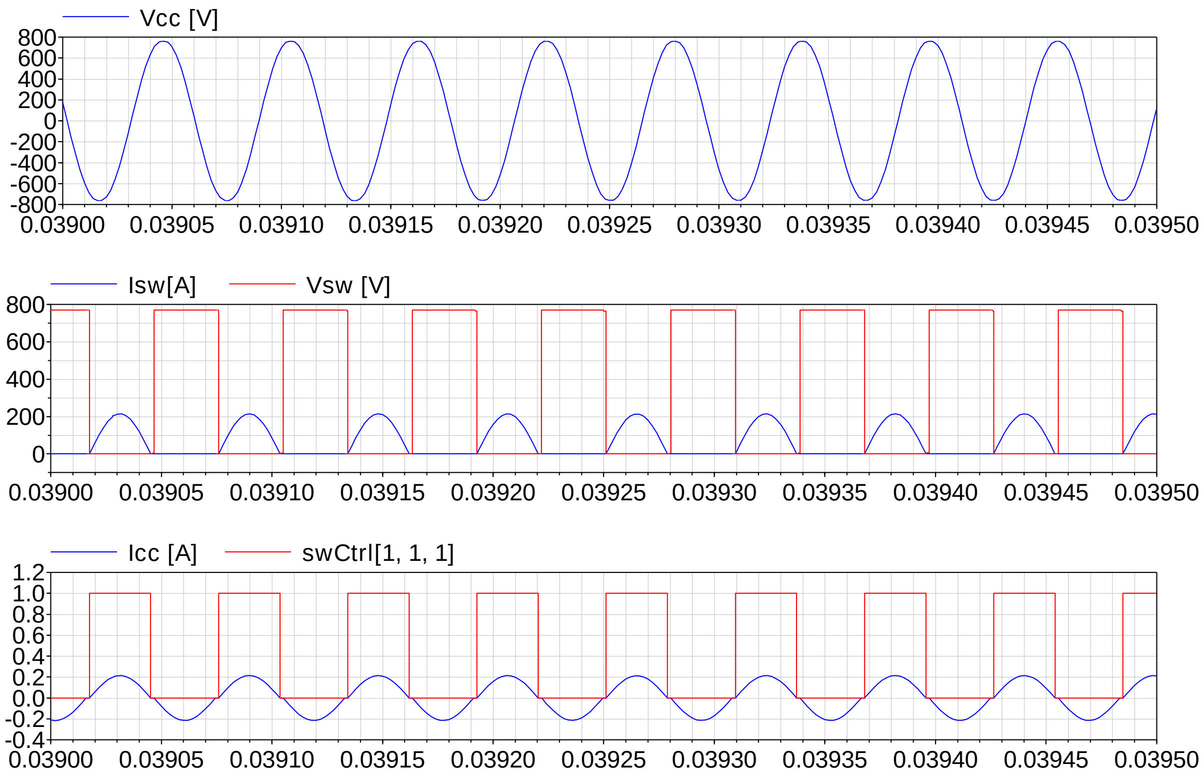

Figure 23: CRL Waveforms - Central Capacitor Voltage / Current and Transformer Voltage, Central Capacitor Current and Triggering

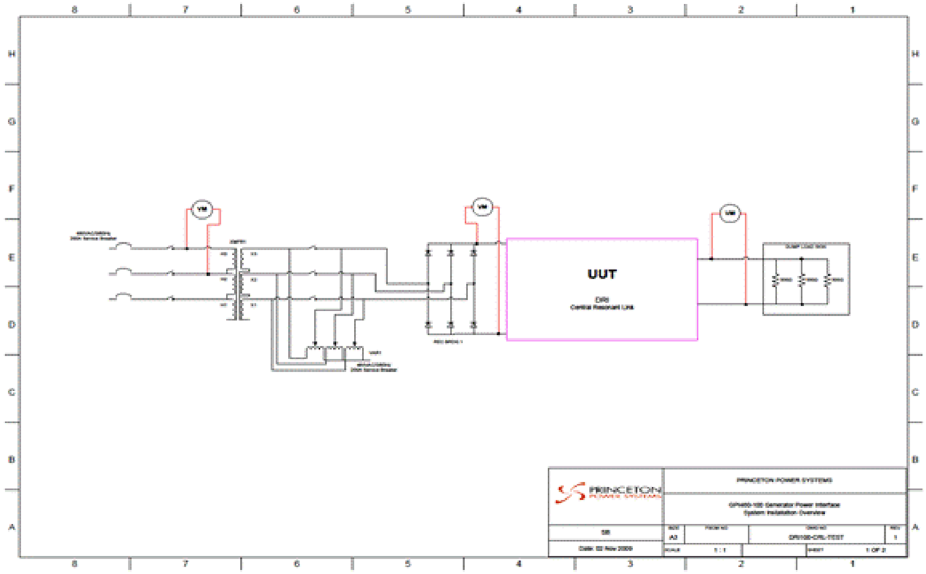

Figure 24: CRL Benchtop Test Bed Schematic

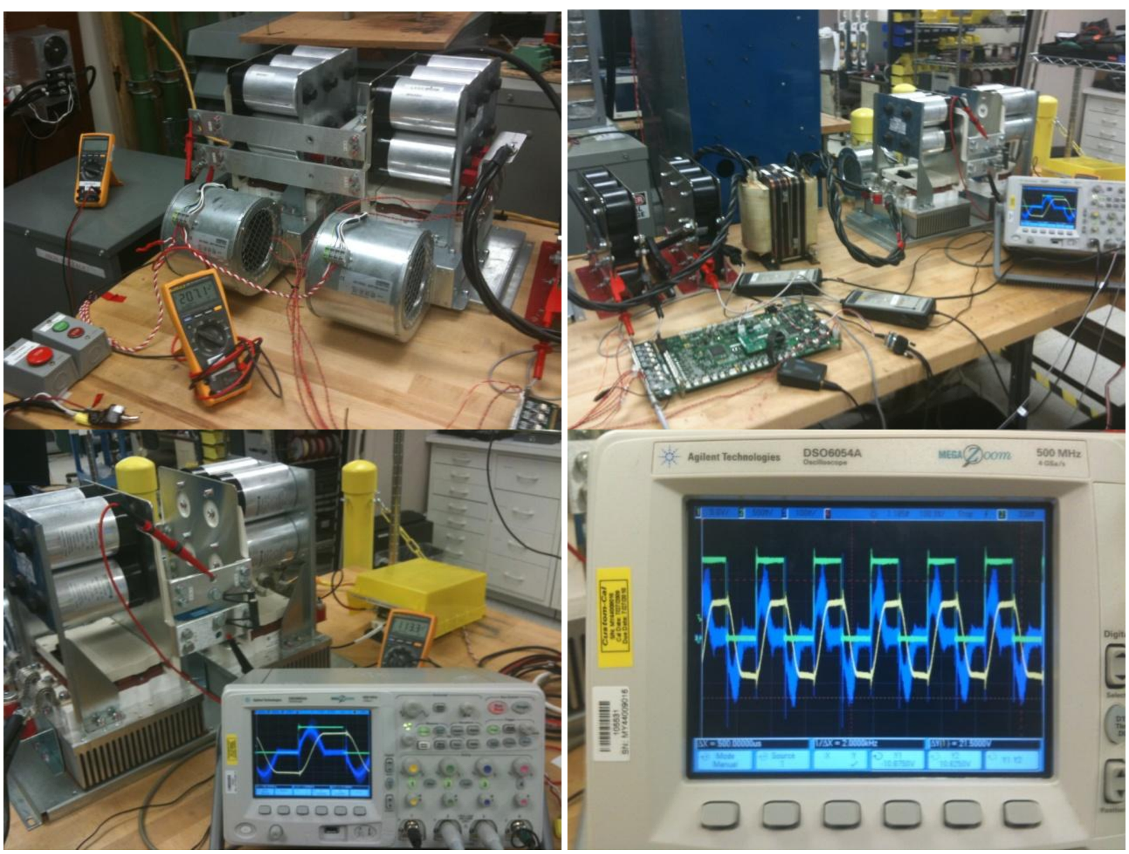

Figure 25: Central Link Test Bed Unit under Test

Table 1: CRL Bench-top Test Results

Load	10	ohms			
Input Voltage (V)	Output Voltage (V)	Amps Calculated (A)	Amps Actual (A)	Power Actual (W)	Central Link Peak Amps (A)
15	15	1.5	1.5	22.5	1.6
20	20	2	2	40	1.9
25	25	2.5	2.5	62.5	2.6
50	45	4.5	4.5	202.5	4.6
55	54	5.4	5.4	291.6	5.4
60	57	5.7	5.8	330.6	5.8
65	60	6	6.1	366	6.1
75	70	7	7.2	504	7.2
80	78	7.8	7.9	616.2	7.9
85	83	8.3	8.3	688.9	8.3
90	88	8.8	8.8	774.4	8.8
100	98	9.8	9.8	960.4	9.8
110	108	10.8	10.9	1177.2	10.9
120	118	11.8	11.9	1404.2	11.9
130	128	12.8	12.7	1625.6	12.7
140	138	13.8	13.9	1918.2	13.9
150	148	14.8	14.9	2205.2	14.9
160	158	15.8	16	2528	16
170	168	16.8	16.5	2772	16.4
180	178	17.8	17.9	3186.2	17.9
190	188	18.8	18.9	3553.2	18.9
200	198	19.8	19.9	3940.2	20
220	218	21.8	22	4796	22
240	238	23.8	23.9	5688.2	23.9
260	258	25.8	25.9	6682.2	25.9
280	278	27.8	28	7784	28
300	298	29.8	30	8940	30

5.5.4. Central Resonant Link Risk Reduction Testing 100kW @770VDC

5.5.4.1. Test Objective

1. Demonstrate High Frequency Transformer operation up to 100kW @770VDC, 20kHz switching frequency.
2. Max temp rise on the Transformer shouldn't exceed 125C at full power
3. Demonstrate by directional power flow through the CRL. The power would be flowing from the grid port to the battery port and vice versa.
4. Demonstrate Di-electric integrity of CRL circuit (bridge and Transformer)

5.5.4.2. Overview

The purpose of the CRL test was to bring up the CRL section of the DRI to full power and full voltage. The CRL is a soft switching high frequency transformer link that provides the required isolation for grounded DC and AC power converters. For testing purpose the CRL was installed in a dual GTI test setup (Figure 26).

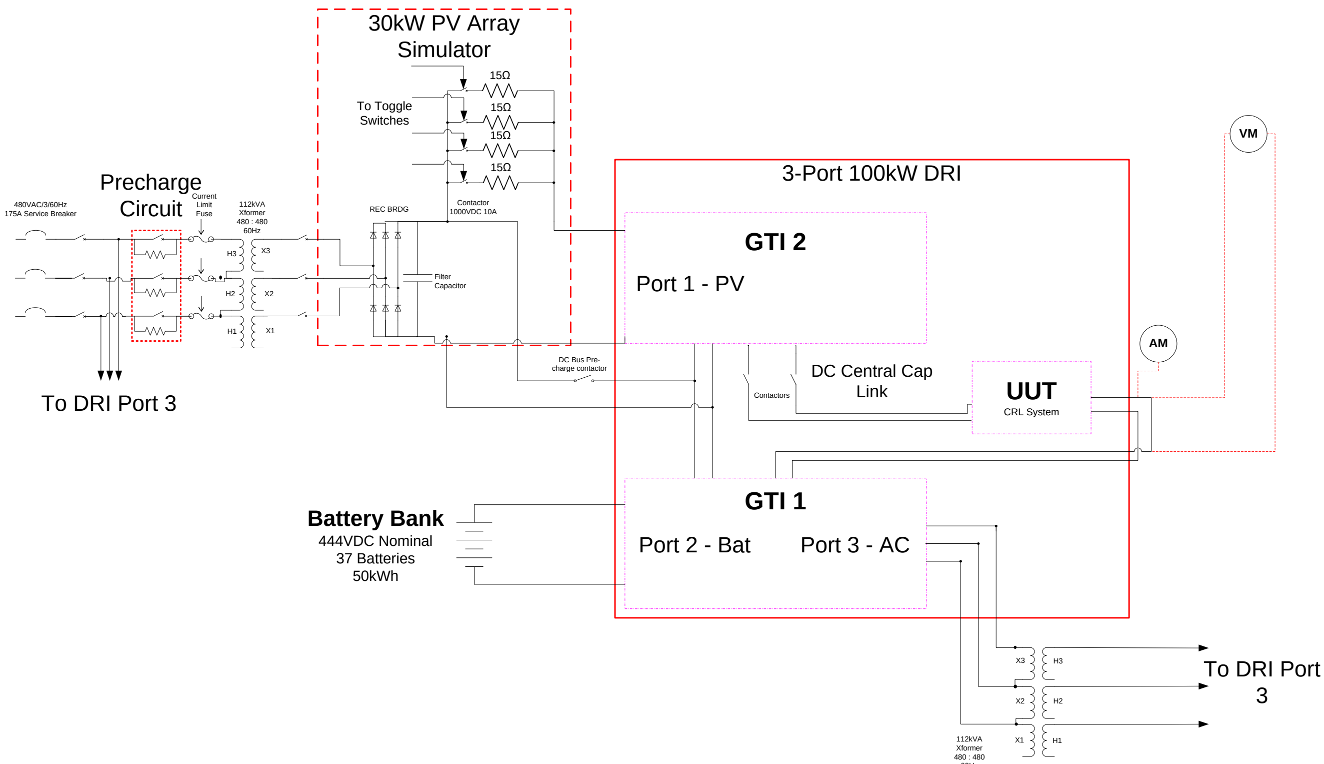

Figure 26: CRL Test Schematic

5.5.4.3. Test Equipment

CRL test equipment is described in Table 2.

Table 2: CRL Test Equipment

Item	Characteristics	Manufacturer	Model	Qty
2	High Voltage Probes 1000:10	Probe Master		4
3	High Amp CT	Fluke		2
1	Thermal Camera	FLIR		1
4	Digital Thermal Meter	Fluke	Fluke True TMS	2
5	100MHz Oscilloscope with	Semikron SEMIX		2
6	Digital Multimeter	Fluke	True RMS 177	3

5.5.4.4. Set-up

- Dielectric test on transformer up to 3080VDC with respect to ground and primary to secondary.
- Dielectric test on CRL setup up to 3080VDC with respect to ground and between input and output.
- Provision of 170CFM airflow through dual fans on the CRL transformer.
- Verification of control cables
- Verification of transformer dot orientation.

5.5.4.5. Procedure

- Set up UUT within dual GTI setup as per schematic.
- Connect control board v2.2 with CRL_SB code to the Semikron bridges.
- Apply 24VDC power to control board.
- Apply 15VDC power to trigger module. You should see 15VDC on the DC capacitors as well. This is caused by bleed current through the trigger module.
- Without any voltage on the DC bus, check for trigger synchronization between phases and check applied voltage on transformer. This is a 15V square-wave and is synchronized across both ends of the transformer. During this test PPS tuned inductance on the CRL to meet proper LC time constant.
- Setup GTI to load 5KW power.
- Turn ON pre-charge and pre-charge both DC link capacitors through CRL. CRL will pre-charge up to 600VDC within 2 seconds. (Figure 27 shows CRL at full power.)
- RUN GTI to draw 5kW power. Measure temp on transformer.
- Ramp power steadily up to 100kW measuring all mentioned parameters.

5.5.4.6. Pass-Fail STOP Criteria

- Over Voltage

  Stop Test if Voltage across single Central AC Capacitor is above 400V peak.
- Over Current

  Stop Test if Current through Central Link is over 212Arms.
- Over Temperature

  Stop test if Transformer winding Temperature is over 125^{o}C.

Stop test if Transformer Core Temperature is over 125°C.
Stop test if capacitor Temperature is above 80°C.
Stop test if CRL IGBT heat-sink temperature is above 90°C.

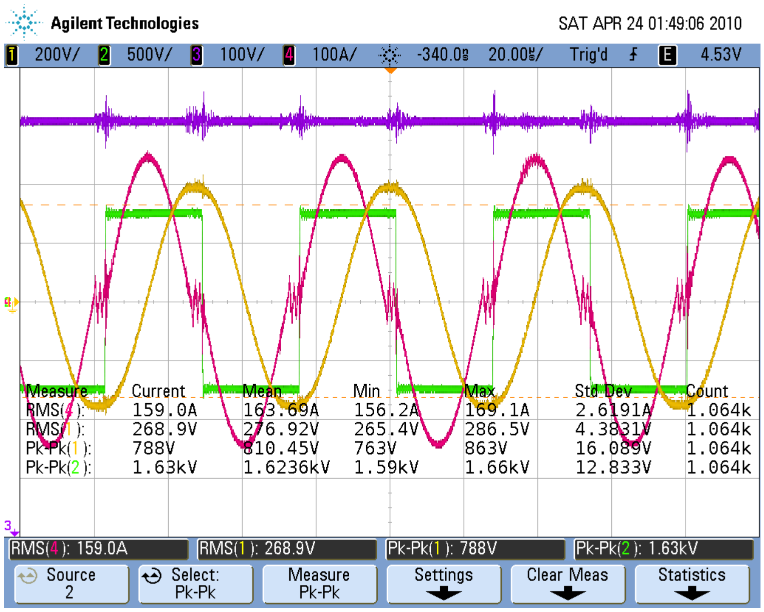

Figure 27: CRL at Full Power

5.5.5. System Functional Tests with CRL

5.5.5.1. System Transient Delay with CRL

In Stage 2 two transient tests were performed using the DRI running with 100kW available battery power in Demand Response (DR) mode: a step change from 0-100kW in grid output power and a step change from 100-0kW. In the scope displays in Figure 28, green represents a single phase of grid current and pink a single phase of voltage. The Logic Analyzer shows the 3 phase voltages and current sinusoids, superimposed with the blue power command signal, whose step change indicates the start of the transient event (Figure 29).

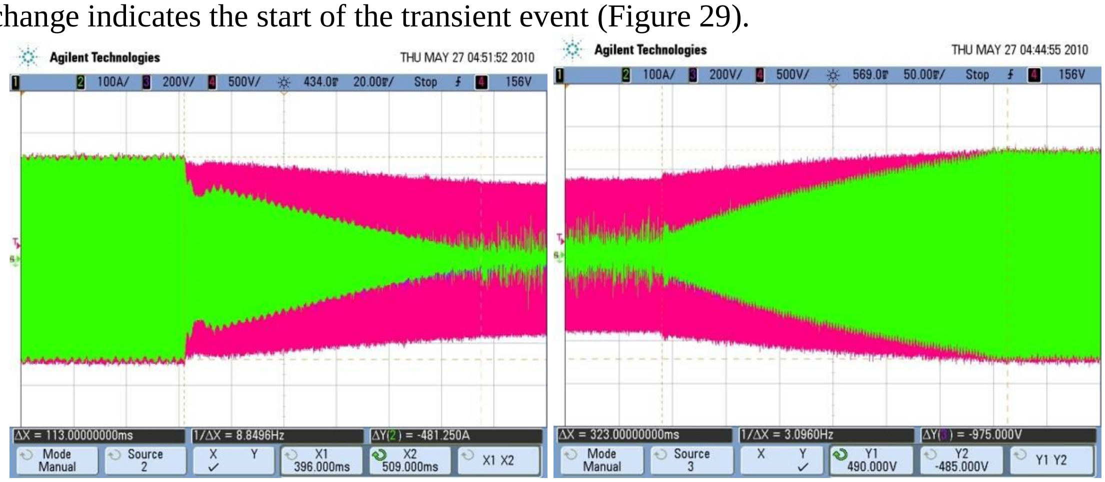

Figure 28: Transient Response with CRL, Turn On/Turn Off

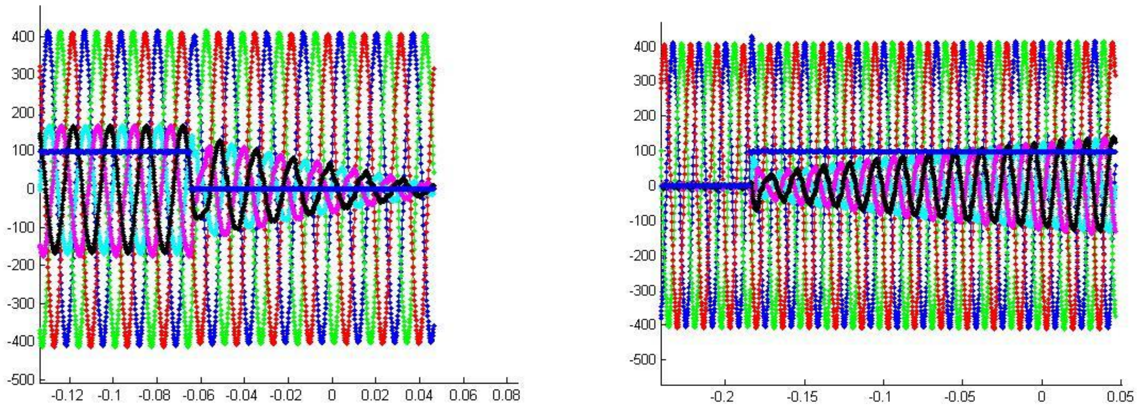

Figure 29: Step Change Results Step Down (Left) and Step Up (Right)

From this we conclude the following:

100 Step Change Result with CRL in situ	
Step Up Time	323 ms (< 20 Cycles)
Step Down Time	113 ms (< 7 Cycles)

5.5.5.2. System Power Quality with CRL

Between the above transients, a steady state capture was made of the running conditions (Figure 30).

100kW Battery to Grid, DR Mode		
DC Bat Voltage	446	VDC
DC Bat Current	246	ADC
DC Bat Power	110.4	kW
AC Grid Voltage	497.8	Vrms, L-L
AC Grid Current	119	Arms, L-N
AC Grid Power	103.2	kW
Efficiency	93.5	%
Ithd	1.96	%

Figure 30: Power Quality Test Results

5.5.5.3. Noise Measurement of System with CRL

80 dBA SPL@1m with all four bridges running in DG mode.

5.5.5.4. VSD Operation - Transient Analysis

Setup:

- System running with 40kW available power in DG mode
- 50Hp Motor-Genset connected with 35kW resistive load
- No battery connected
- Grid connected, but not providing power

For this test, the system started at full available PV power (40kW), which was reduced in 10kW increments. The motor function is designed to reduce output voltage and frequency (constant V/Hz control) as available PV power dwindles.

Result:

- 92.53% Efficiency at 40kW

Conclusion:

- Central-resonant link circuit is bidirectional.
- HF transformer provides compact and light weight solution to bulky galvanic isolation needs.
- HF transformer design is verified to operate at 20kHz.
- Switching of primary inverter and secondary rectifier operation is verified.

While the bench-top testing was successful in proving that the concept is viable, more work is required to make this technology production ready. We are currently looking at various manufacturers who can reliably and repetitively produce the toroidal transformer.

In Stage 2 the design suffered from high core and winding temperatures under full power during testing that brought serious concern for product safety and reliability.

In Stage 3 it was decided to go to production using a standard 60hz transformer for reliability; however the CRL is still part of an ongoing research and development effort that may end up in standard production units in the future. A prototype version is planned for installation in one of the seven Stage 3 pilot units.

5.5.5.5. Stage 3 Design Revisions

While previous testing of the first CRL design validated its use as a galvanic isolator, it also proved the design inadequate for use in production DRI units due to excessive heating and high component costs. As a result, the following improvements were made:

- Switched to larger diameter litz wire winding to reduce copper losses and decrease the number of necessary conductors.
- Switched to an ETFE wire jacket in place of kapton tape to reduce wire manufacturing costs.
- Reduced number of turns to ease manufacturing and, as a result, reduced the leakage inductance. Capacitance was adjusted to preserve resonant behavior.
- Added an irradiated aluminum potting box to ease installation and promote heat transfer away from the core and windings.

Pictures of this new design are shown in Figure 31 through Figure 33.

Figure 31: Nanocrystalline Core with Litz Wire Windings

Figure 32: CRL Housing Heat Sink and Mounting Support

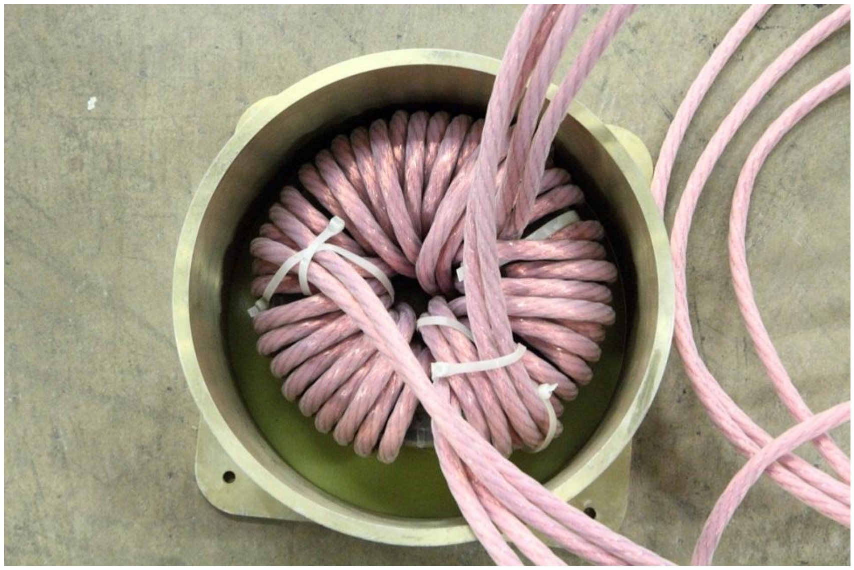

Figure 33: CRL Assembly Prior to Potting

Continued development of the CRL will involve a second risk-reduction bench top test in early 2012 with the following objectives:

- Demonstrate High Frequency Transformer operation up to 100kW @700VDC.
- Test Central Link Hardware for 20kHz DC/DC Operation up to 700VDC input
- Test Central Link Control Algorithms with Integrated v2.5 Control System
- Characterize core and copper losses as a function of switching frequency and DC bus voltage

5.6. Design for Reliability

5.6.1. The Need for MTBF Studies and Its Relevance in Power Electronics

Mean time between failures (MTBF) is a statistical prediction of the elapsed time between failures in a system during operation. The value of an MTBF study is obvious; it provides consumers with an estimated lifetime for a product operating within the intended environment. In utility scale power electronics, MTBF carries increased value, as the estimated lifetime of grid-level systems catalyze many of the business and technical processes of the companies that use such systems. Providing accurate estimates of system life is of great benefit to the manufacturer of those systems and those who intend to use them.

5.6.2. MTBF Measurement Standards and Methodology

The MTBF studies performed on SEGIS hardware by the MTBF consultant, ARA associates, follow the Telcordia SR-332 (Telcordia, 2011) standard [7]. This standard allows the use of the parts count method, a technique that allows for estimating the average life of a whole assembly.

The result of this exercise is the failure rate, denoted FRx (where x is an integer). The MTBF is calculated from the failure rate as follows:

$$MTBF = \frac{1000000000\ hours}{FR1 + FR2 + FR3 + FR4 + \cdots \ldots FRn}$$

The failure rates of the individual components are determined either by referencing manufacturer data or by using the failure rates provided by MIL-HDBK-217, "Military Handbook, Reliability Prediction of Electronic Equipment," (Department of Defense, 1991). The individual failure rates are then summed to provide the net failure rate of the entire unit.

5.6.2.1. Testing Conditions

The test results referenced in this report reflect the predicted life under what is known as Ground, Fixed, Controlled GB $\pi E=1.0$ conditions. Under these conditions, the parts are assumed to experience nearly no environmental stresses with optimum engineering operation and maintenance. The NEMA 3R standard that the DRI unit is designed to allows for more strenuous operating conditions. But, on the average, the unit will see conditions that are similar to those assumed in the Ground, Fixed, Controlled GB $\pi E=1.0$ standard.

In this study, failure of the entire DRI unit can be instigated by the failure of a single component, no matter the component or its function. Despite this, such a failure may not necessarily constitute the failure of the entire unit when operating in the field. Because of this, the MTBF can reflect a truncated lifespan if interpreted without a comprehensive maintenance schedule. Such a schedule is contingent upon the completion of the second round of MTBF studies and will be presented later in this report.

5.6.3. MTBF Goals for DRI

In keeping with industry standards, the SEGIS unit must meet a minimum of 5 years MTBF. An MTBF of 8 to 10 years, with properly scheduled maintenance, is preferable.

5.6.4. MTBF Study Results

5.6.4.1. Initial Study Results

The first study undertaken by ARA associates produced a result of 1.4 years between failures of the SEGIS DRI—a number far below the target. Examination of the data revealed that the high failure rate was not a systemic problem. Indeed, the DRI's poor initial performance was traced to a small number of components, the majority of which were control system components that had extremely high individual failure rates, high quantities of components with medium-range failure rates, or components that were incorrectly analyzed due to poor assumptions concerning the parts' duty cycles and operating conditions. Of note is the high MTBF for the power electronics power train. The study predicted approximately 58 years between failures of the components transferring power.

Problem Components
The least reliable components within this initial study reside primarily within the control system. Those control system components are:

- Control Board (PCB1)
- Peripheral Board (PCB2)
- Communication Board (PCB6)
- Ground Fault Detection Interrupt (GFDI) Board (PCB10)
- Converters/Isolators
- The four DC/DC power supplies

In sum, these components contributed heavily to the reduced MTBF estimate of the system from the powertrain estimation of approximately 58 years to the unacceptable 1.4 years.

5.6.5. Steps to Improve MTBF

The breakdown of the performance of individual components allowed PPS to create performance improvement goals for the worst performers. Two different sets of MTBF estimate goals were created, one set for a five-year MTBF rating and another for a 10-year MTBF rating. These goals helped identify individual parts that required replacement, while also allowing PPS to view and assess the reliability performance of the DRI from a holistic perspective.

5.6.6. Results

Significant improvements were achieved in the MTBF ratings of the control board, GFDI board, and the Peripheral board by reviewing and replacing commercial rated parts with industrial or military grade parts. The original communications board was replaced with a completely different design, and the converters/isolators, contactors, case switches, and fused disconnects were upgraded. Every one of these improvements met or exceeded the 5 year MTBF target, increasing the MTBF of the entire unit in the process. When a second study was performed with the updated component results, the MTBF of the entire unit increased to 8.395 years, a significant improvement reflecting the improved design and selection of the components in question.

5.7. Product Specifications

Demand Response Inverter (DRI)

PRINCETON POWER SYSTEMS

Princeton Power Systems
Clean power made simple.™

Demand Response Inverter (DRI)
3-Phase, Grid-tied, Controllable 4-Terminal Power Conditioner

Decrease Demand

Princeton Power's bidirectional Demand Response Inverter is designed to reduce the Levelized Cost of Energy (LCOE) of photovoltaic (PV) power by being more efficient, more reliable, and more cost-effective than currently available inverters. The DRI will provide valuable grid-support functionality that allows for high penetration of PV power systems into the electric grid and added value for the system owner and local utility.

Efficient | Maximize power.
Maximize power and minimize cost.
Improve energy conversion efficiency with DRI's evening auto-disconnect and daytime auto-power-up capabilities. Programmable power curves and charge profiles also provide enhanced control for generators and AC loads.

Reliable | Eliminate downtime.
Eliminate downtime and decrease demand.
Reduced failure rate, increased lifespan, and advanced, high-capacity switches allow the DRI to provide back-up power in times of need and during peak demand.

Flexible | Integrate quickly and easily.
Highly compatible and easily integrated.
E-QUAD Technology allows power routing to the grid, DC energy storage, and dynamic AC loads. It's bi-directional AC grid and DC energy storage connection terminal makes the DRI ideal for micro-grid/off-grid applications.

E-QUAD™ Power Flow Control Technology
Dynamic control of four bi-directional loads/sources through a central high-frequency link

Features & Options

- Five (5) Smart Relays automatically shed low-priority loads in the event of power loss, or in response to price signals and grid needs
- Ground fault detection and interruption (GFDI)
- Front-panel keypad and touchscreen display
- Web-based performance monitoring, data logging, control, fault clearing, firmware upgrades
- Revenue-grade kWh meter (optional)
- Manual AC and DC disconnects and combiner box (optional)
- Utility interface communication modules for IEC 61850, Modbus, and CANbus

PRINCETON POWER SYSTEMS

Princeton Power Systems
Clean power made simple™

Demand Response Inverter (DRI)

3-Phase, Grid-tied, Controllable 4-Terminal Power Conditioner

Princeton Power DRI

GENERAL SPECIFICATIONS	
Inverter Technology	High-frequency PWM
Size Inches	36 W x 18 D x 75 H
INPUT SPECIFICATIONS	
DC Voltage	280 — 750 VDC (above 600 VDC not UL Certified)
DC Maximum Power Voltage	330 — 750 VDC (above 600 VDC not UL Certified)
PV MPPT	280 — 580 VDC
PV Array Configuration	Transformerless: Ungrounded With Optional Isolation Transformer: Monopole positive or negative grounded or bipolar neutral grounded
DC Voltage Ripple	< 1%
GRID CONNECTION PORT SPECIFICATIONS	
AC Line Voltage	480 VAC +10%, -12%, 3-phase
AC Line Frequency	60 Hz nominal 57-60.5 Hz range (field adjustable)
Continuous AC Current	133 A RMS
Continuous AC Power	100kW
Power Factor	>0.95 above 20% rated power
Current Harmonics	IEEE 1547 Compliant, <5% THD
AC OUTPUT PORT SPECIFICATIONS	
AC Output Voltage	480 VAC +10%, 3-phase
Voltage Harmonics	IEEE 1547 compliant, <3% THD (Resistive Load)
Maximum Load Power	100kW
Allowable Load Power Factor	1.00 -0.85 (Lagging)
Maximum Load Current	142A
Backup Auto-transfer time:	To Backup: 250ms To Line: 250ms
ENVIRONMENTAL SPECIFICATIONS	
Temperature Operating	0 to 50°C Storage: -20 to 60°C
Humidity	5 – 95% (non-condensing)
Cooling	Forced-air cooled
Rated Max Elevation	6,000 feet
Enclosure	NEMA 1 (Indoor)
SAFETY FEATURES	
Faults	Over/Under Voltage, Over/Under Frequency, Over Current, Overload, Over-temperature
Standards Compliance	IEEE 1547, CEC, UL 1741 Certified (#720990351.01)
Safety Features	Anti-islanding (grid fault detection, isolation, & auto-reconnect) UL-compliant trip points (field adjustable)
USER INTERFACE FEATURES	
Front-Panel Interface	4x20 LCS, Keypad, Fault LED's
Communications	We offer a wide variety of communications options
Performance Monitoring	Real-time & Historic, web-based performance data
Analog & Digital I/O	Analog: (3) inputs, (1) output; 0-10 V or 4-20 mA Digital: (3) inputs 0-24V, (2) output relays
EFFICIENCY	
Peak Efficiency	96.5%
CEC Efficiency	95.0%
Nighttime TARE Losses	25 W
Energy-saving Features	Automatic internal subsystems power-down, Nighttime transformer auto-disconnect
Energy-Saving Features	Automatic internal subsystems power-down, Nighttime transformer auto-disconnect

About Princeton Power

Princeton Power Systems designs and manufactures high-performance power electronic converters and systems for commercial, industrial, and military distributed generation applications.

Specifications subject to change without notice, contact manufacturer for updated information.

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info@princetonpower.com • Press Inquiries: press@princetonpower.com • Sales: sales@princetonpower.com
www.princetonpower.com

Figure 34: DRI Product Specification

6. MANUFACTURING AND TEST FACILITY

6.1. Production Facilities

PPS now has commercial-scale assembly lines that consist of an assembly area, production-test and burn-in stations, shipping/receiving space, and raw materials and finished goods inventory space, as shown in Figure 35. Production will occur at the 10,000 sq. ft. facility at 3175 Princeton Pike, Lawrenceville, NJ 08648. The facility has a 1000 amp electric power service and a skilled labor force, as well as strong state incentives for expanding manufacturing and job creation.

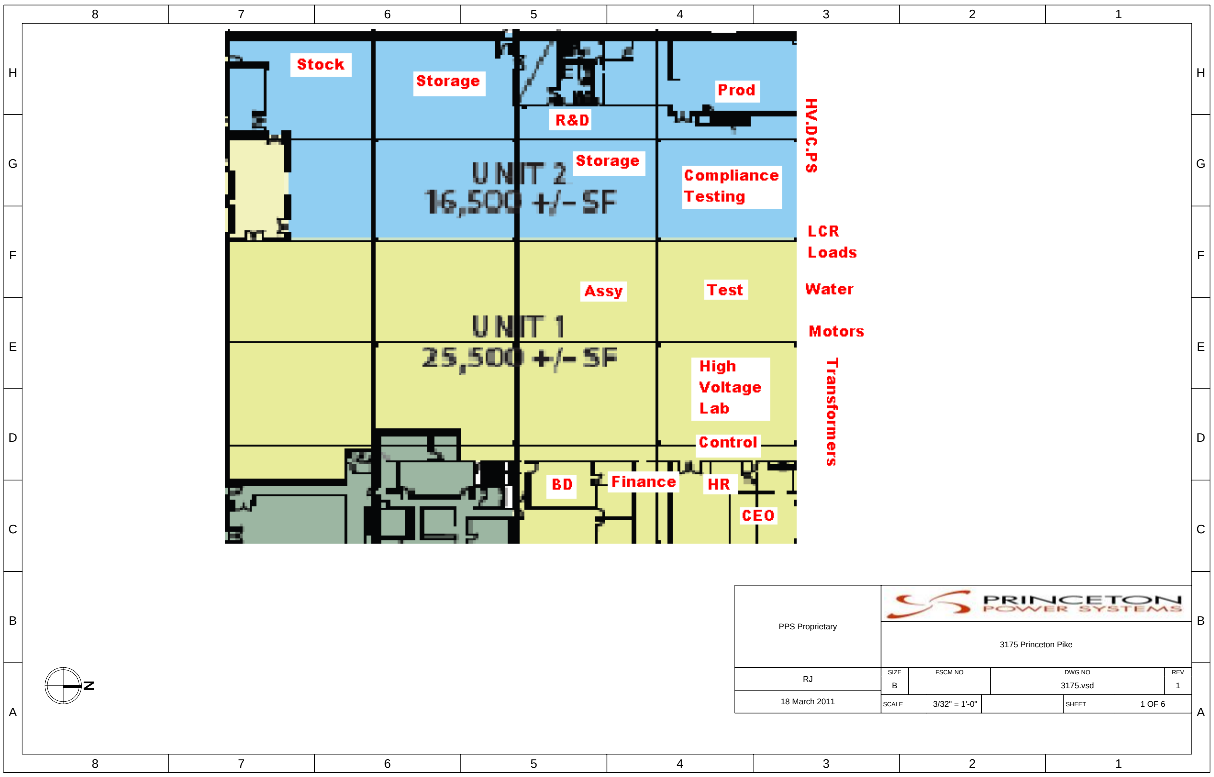


Figure 35: The 3175 Princeton Pike Facility Layout

6.1.1. Raw Material Inventory Area

Incoming inspection and test starts when items are received at the loading dock. A Materials Acceptance Form (MAF) is created at the time of a purchase order request that specifies what is to be tested or inspected. Most testing occurs in the Printed Circuit Board (PCB) room. Once the received part passes inspection, the item is stored in our controlled stockroom (Figure 36). If an item does not pass, a Returned Material Authorization (RMA) is created and the item returned. This MAF system is integrated into the PPS purchase order system.

Figure 36: Controlled Stock Room

6.1.2. Manufacturing Facilities Details

Each Demand Response Inverter (DRI) assembly station shown in Figure 37 occupies 100 sq. ft. of floor space. Two round-the-clock assembly stations are set-up at present. For a small batch production, each unit currently requires 200-hours of assembly time with two technicians working in parallel; six assemblers each working eight-hour shifts can produce 64 units per year.

Figure 37: DRI Assembly Area #1

6.2. Production-Test Facilities Details

The functional factory acceptance test (FAT) and Burn-in test station is set up to test either one 100kW DRI or two 100kW GTIs. Each unit undergoes a 12-hour functional and burn-in test. Running year-round at full capacity (double-shifts), the test bay can accommodate 6570 hours of testing (taking into account 20% downtime for setup, equipment maintenance, etc.) this enables testing a maximum of 547 units annually. The test bay itself requires 200 sq. ft. of floor space, including equipment and standoff space. For PCBs and sub-assemblies, an additional 200 sq. ft. of flex space is also available. There are also various bench-top test setups for different subassemblies (Figure 38). The power requirement for one burn-in or testing station (Figure 39) is 200kW circulated. Testing will leverage recirculation so power consumption during burn-in is minimized (based on efficiency). A “Buss Way” system can deliver up to 600A at 480Vac. A second system of 1000A is currently being installed for larger systems.

Figure 38: DRI Bench Top Test Setup

Figure 39: Test and Burn-In Area

6.3. Finished Goods Inventory Area

The northwest portion of the building is set aside for "Finished Goods". This Storage area (shown in Figure 40) is flexible, as the shop floor can expand or contract with orders. Finished goods can also be stored vertically or outside in special trailers. As PPS builds to stock, they do not anticipate long storage of complete units, so this area remains fluid. Vertical racks can store finished units at the floor level, and the warehouse can use racking above them.

Figure 40: Finished Goods Inventory Area

6.4. Shipping/Receiving Area

Shipping and receiving is between the stock room and the loading dock door as shown in Figure 41. DRI units can be unloaded, brought in, or packed and shipped in this area. A forklift can move a unit to a loading dock from test with ease.

Figure 41: Shipping and Receiving Area

Based on this, the total floor space required to produce a maximum of 64 units annually is shown in Table 3.

Table 3: Production Facility—Facility Space Set-up for Production and Test @64 Units per Year

Area	Sqft	# of Areas	Total sqft
Raw Materials Inv	1,500	1	1,500
Assembly Space	100	2	200
*Test Bay I	200	2	400
PCB Test Station	200	1	200
Bench Top	20	2	40
*Finished Goods Inv	1,000	1	1,000
Shipping/Receiving	1000	1	1,000
TOTAL			**4,340**

7. TEST PROGRAM

7.1. Program Overview

The test program is outlined below. Note that numbers are intended to sequence tests, although they represent an ideal rather than necessary progression of development. The group of tests under a particular subsection is referred to with a number divisible by 10; hence "100" tests refer to all individual tests between 101 and 190, etc.

The System Verification Test was to type test the first prototype unit and to confirm that system operation met or exceeded the product specification. It comprised the following categories of tests:

- 100: Design Improvement Validation
  These tests were to validate changes to the Power Electronic (P.E.) design implemented in Stage 2.
- 200: Control Component Validation
  These type tests were to validate changes to the control system PCBs implemented in Stage 2.
- 300: Subsystem Integration
  These type tests were to bring up the first unit at subsystem-level increments, and then to validate the performance of subsets of power ports working together until operation with all four ports achieved.
- 400: First Article Test
  These type tests were to thoroughly evaluate the performance of the system as a whole to confirm the internal specification.
  - 410: Fault Protection
  - 420: User Interface
  - 430: Software Functionality
  - 440: Continuous Operation
  - 450: Environmental
  - 460: Reliability

The compliance test program follows and comprises the following tests:

- 501: UL1741-2010 [6] compliance certification
- 502: IEEE 1547.1 [8] (the grid interface standard as referenced by UL1741)
- 503: CEC listing
- 504: FCC Part 15 Class A compliance certification

The production test program comprises the following tests

- 601: Unit 1 prototype test, used to define the production test scope
- 602…607: Units 2-7 production tests

The Field Demonstration program was performed on September 28, 2011, and was planned and managed by the test department at a technical level. The demonstration set-up and plan is also intended to be repeated for the benefit of other customers and interested parties.

- 701: Field Demonstration

7.2. Summary of Results

The test program for the DRI will result in a UL-1741 and FCC compliant product, with CEC listing. Having demonstrated effective operation as part of a prototype in Stage 2, the primary testing objective for the DRI in Stage 3 of the SEGIS program was to gain sufficient confidence that the first article met the internal specification as released at the start of this project. This objective excluded certification itself but required that at the end of Stage 3 a reasonably low technical risk remained in choosing to pursue certification. PPS believes that this objective has been substantially met, although some tests remain.

The testing program relied on validation of pilot production units and the development of an internal quality assurance (QA)/production manufacturing test. So far, three pilot units have been completed: one for beta testing at PPS's solar field, and two to be delivered to beta sites for further on-site beta testing. All have undergone the final QA test. An additional four pilot units are in production; they are to be used for UL certification, environmental and reliability testing, and additional beta site testing as required.

Unit 1 underwent the System Verification Test to recognize changes present in the design since Stage 2, first at the component level, then the subsystem integration level, and finally at the system level. Unit 1 was then installed at PPS's solar demonstration site, and units 2 and 3 have been tested to the system level and will be deployed at additional partner beta sites.

7.3. 100: Design Improvement Validation Test Report

7.3.1. Overview

The purpose of these tests was to evaluate any intended design changes. At the end of Stage 2, multiple ideas were proposed as possible improvements. Further design analysis, such as that of cost, market desirability, and practicality led to the following tests being identified as requiring further testing:

- 101: Acoustic improvements: 7 dB (A) at full power from first application of acoustic foam. Further improvements were identified by increasing mean noise path length and decreasing radiating surface area.
- 102: CRL: Transformer design was changed for superior thermal performance and reduced leakage inductance. This test has not yet been performed, but is anticipated in the near future.

7.3.2. 101: Acoustic Noise Reduction Test

7.3.2.1. Overview

The SEGIS DRI presents unique and difficult noise issues because a number of sources within the cabinet produce loud noises with distinct characteristics. The aggregate effect had proven to be a concern in the Stage 2 testing of the DRI when the sound of the unit running at full power was measured at 85dB. As a result, acoustic noise reduction treatments have been engineered and installed in Stage 3 in order to bring the acoustic performance of the DRI in line with industry standards. Some of these changes were design packaging changes in the cabinet to deduce audible noise, and some of the changes were add on features such as sound deadening foam to reduce the noise of the unit.

7.3.2.2. Initial Investigation

In November of 2010, Tom Miller of Noise Unlimited Labs measured a single GTI (Grid Tied Inverter) and a SEGIS DRI Stage 2 cabinet (with fans only). A 1/3 octave band analyzer was employed to help PPS quantify the acoustic behavior that the SEGIS Stage 3 DRI might display. The results of his efforts are summarized in Figure 42. Note that the measurements are raw data and are uncorrected (no A-weighted modifications).

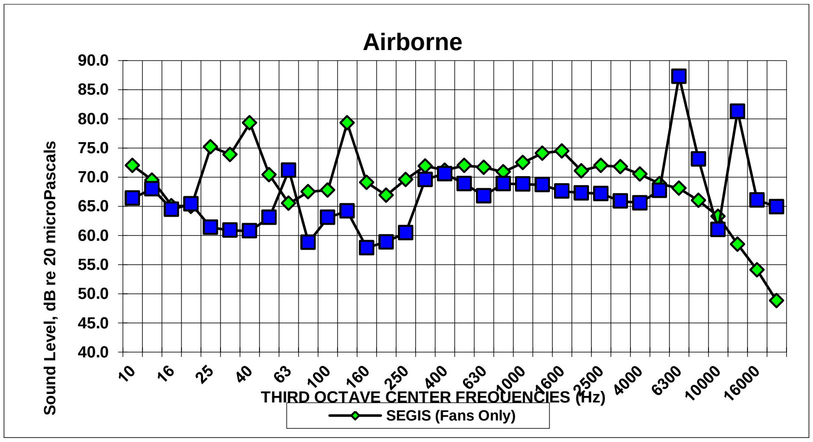


Figure 42: Sound Pressure Level Comparison at Full Power (Green♦ =DRI; Blue■ =GTI)

Figure 42 compares the full power noise generated by the GTI with the fan noise created by the SEGIS Stage 2 unit at full speed. A rough estimate of the performance of a SEGIS Stage 3 unit was obtained by summing the two curves. When considered in conjunction with the negative gain of the A-weighted curve, it becomes apparent that the low frequency peaks in this figure would likely fall below the 65dBA limit or disappear completely once the units are moved and measured in their respective environments. Of concern is the mid-range fan noise and the high-frequency peaks generated by the IGBT switches; these are the sources of noise that were targeted with the Stage 3 redesign and with acoustic treatments.

7.3.2.3. Design Changes

PPS updated the prototype design in Stage 2 and re-designed the layout of the cabinet in Stage 3. The cabinet is a much tighter design and should offer some acoustic improvements. Also, acoustic absorption materials were employed. Acoustic foam, an open-cell foam that adheres to the inside of the cabinet and transforms acoustic energy into heat (thereby reducing audible noise) was installed in one of the Stage 3 units for comparison testing on the effectiveness of using the acoustic foam in this application.

Acoustic foams have been heuristically proven effective for similar applications and can produce large reductions in audible noise, sometimes on the order of almost 20dB. Though the DRI cabinet adheres to the same laws that govern noise reduction in rooms, the measurements needed and calculations used to estimate noise reduction performance are difficult to manipulate under the conditions present in this cabinet.

The recommended foam provides no increase in absorption over the enclosure walls below about 350Hz, at which point noise reduction increases to a maximum of about 18dB between 1700Hz and 4000Hz. The absorption then decreases to about 14dB for higher frequencies. Note that data for the foam's behavior after 4000Hz is not available at this time. The average behavior over the foam's application range was used to estimate the behavior above 4000Hz.

Looking at the A-weighted curve, the low frequency noise becomes a non-issue, as does the mid-frequency noise produced by the fans. The high frequency whine created by the IGBT switches is still above the maximum allowable, with the peak frequency at 6300Hz reaching almost 80dB_A. This suggests that the whine will be the most troublesome noise to reduce but does not mean that the selected foam is ineffective.

As per the recommendations from the acoustic noise consultant, the DRI unit was treated with half-inch thick, open cell foam with black matte surface finish and self-adhesive backing shown in Figure 43. Maximizing coverage during the first iteration was attempted in order to measure the greatest possible noise attenuation in the least amount of time. Nearly every bare surface inside the cabinet and the exhaust plenum was covered with foam. The pictures in Figure 43 detail the installation process, showing foam installed in various locations.

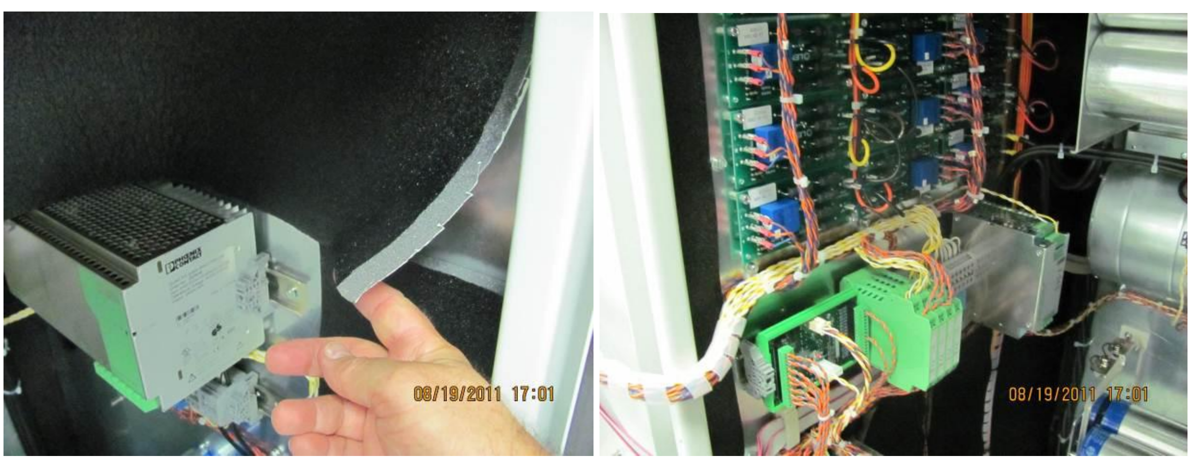


Figure 43: DRI Absorbent Foam Installation

7.3.2.4. Acoustic Noise Testing

In order to accurately measure acoustic noise produced by the DRI, two DRI units were tested. One was treated and another untreated in order to get a baseline for the Stage 3 design and understand the effects of the acoustic treatments.

Acoustic Test Setup

Acoustic testing of the DRI design utilized two separate DRI units, one treated and one untreated. The untreated unit was located outdoors at the PPS Solar Field beta site. The foam treated unit was located inside the PPS production facility.

A-Weighted SPL Measurements

A-Weighted measurements were taken of an untreated SEGIS unit at 1 meter away from the front, center door, with the microphone 4.5 feet above the ground. Three rounds of testing were conducted at 10, 50 and 100kW, in order to establish a baseline profile with which to compare a treated unit. The results of both tests are shown in Table 4. All SPL measurements were measured in decibels, and were A-weighted.

Table 4: DRI Acoustic Measurements (A-weighted Average)

A-weighted results (57-61 dB Ambient)			
Power (kw)	Untreated (dBA)	Treated (dBA)	Change (dB)
10	57.56	58.67	1.11
50	68.55	68.25	-0.30
100	75.69	71.69	-4.00

Spectral Measurements

In addition to the A-Weighted measurements, full-spectrum uncorrected measurements were taken of both treated and untreated units. The 10kW, 50kW and 100kW measurements are shown in Figure 44 through Figure 47 (note that measurements in these figures are referenced to 0 dBU and are not to be taken as absolute measurements of sound pressure).

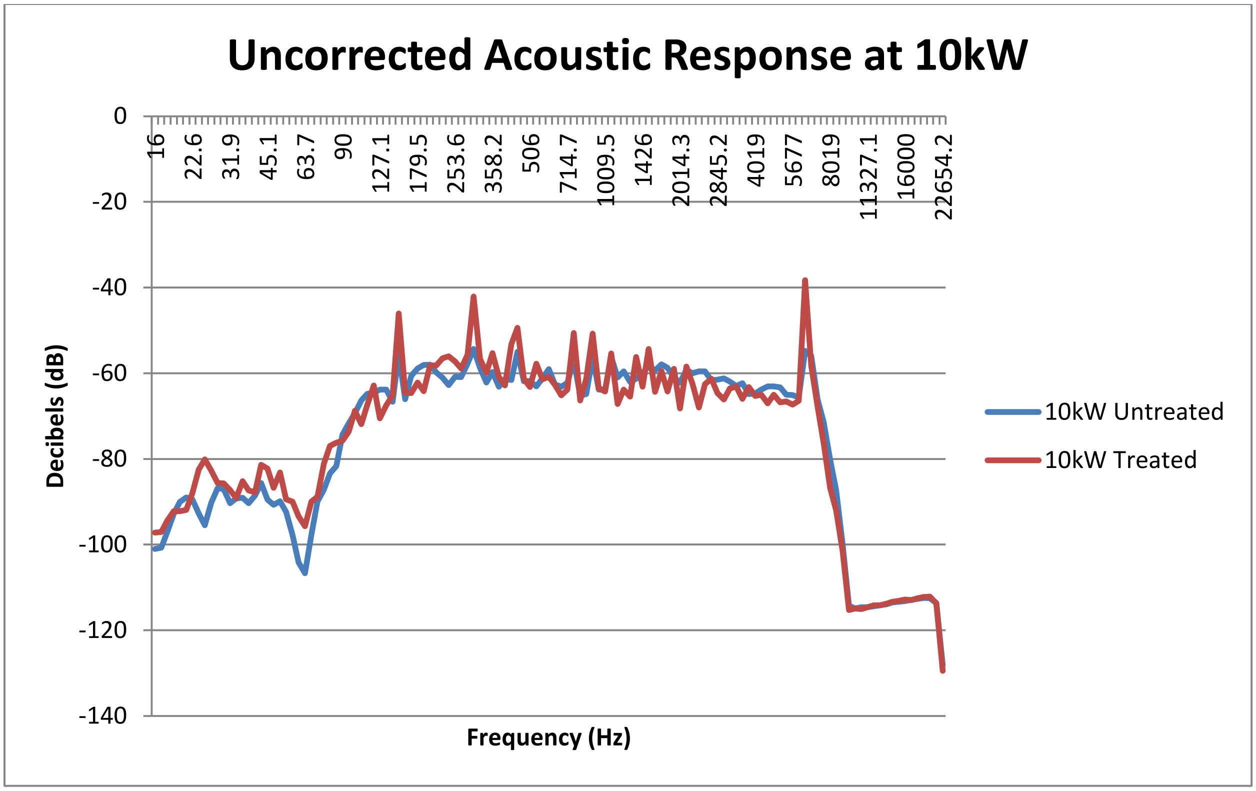


Figure 44: Uncorrected DRI Acoustic Spectral Measurements at 10kW

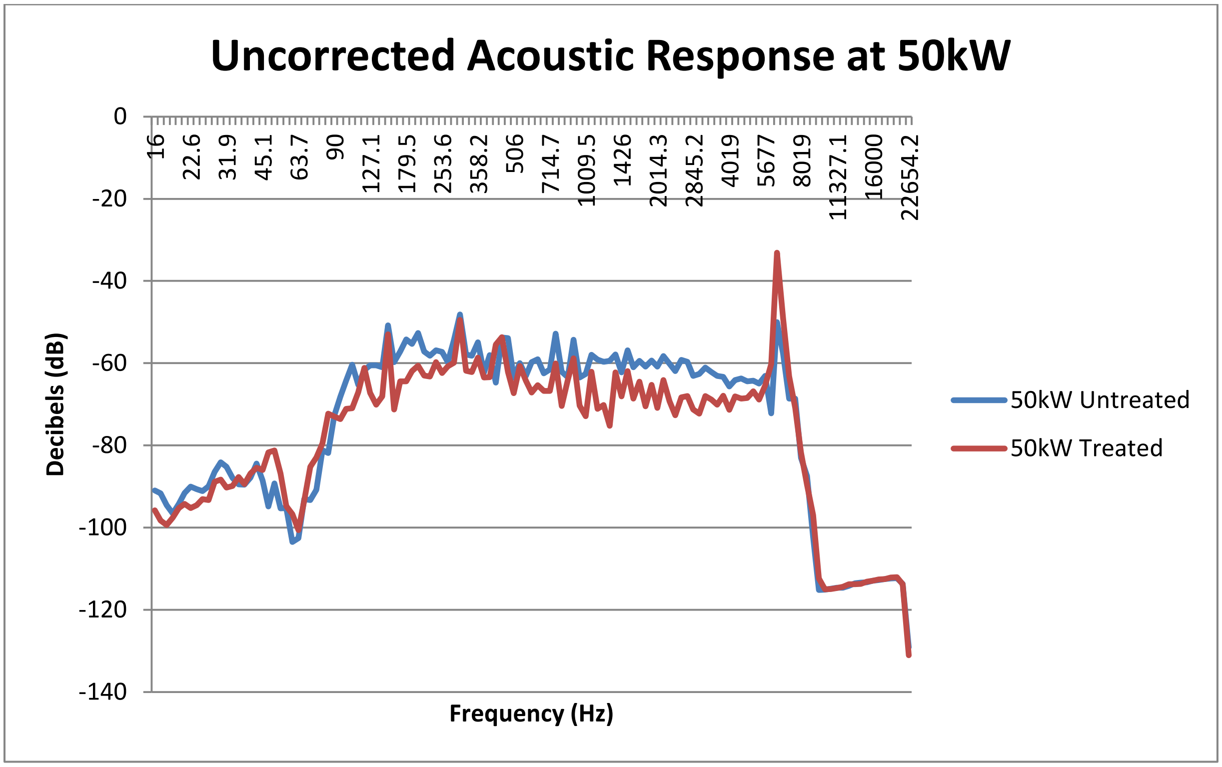


Figure 45: Uncorrected DRI Acoustic Spectral Measurements at 50kW

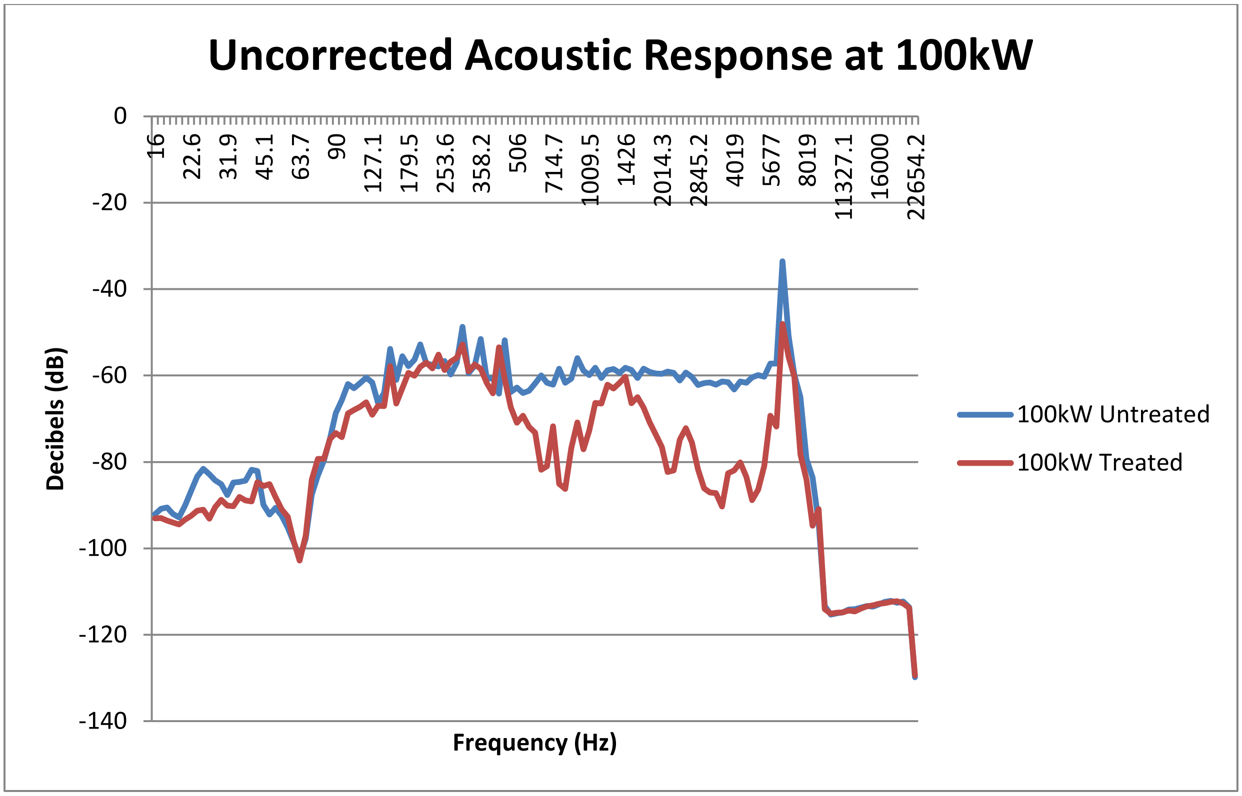


Figure 46: Uncorrected DRI Acoustic Spectral Measurments at 100kW

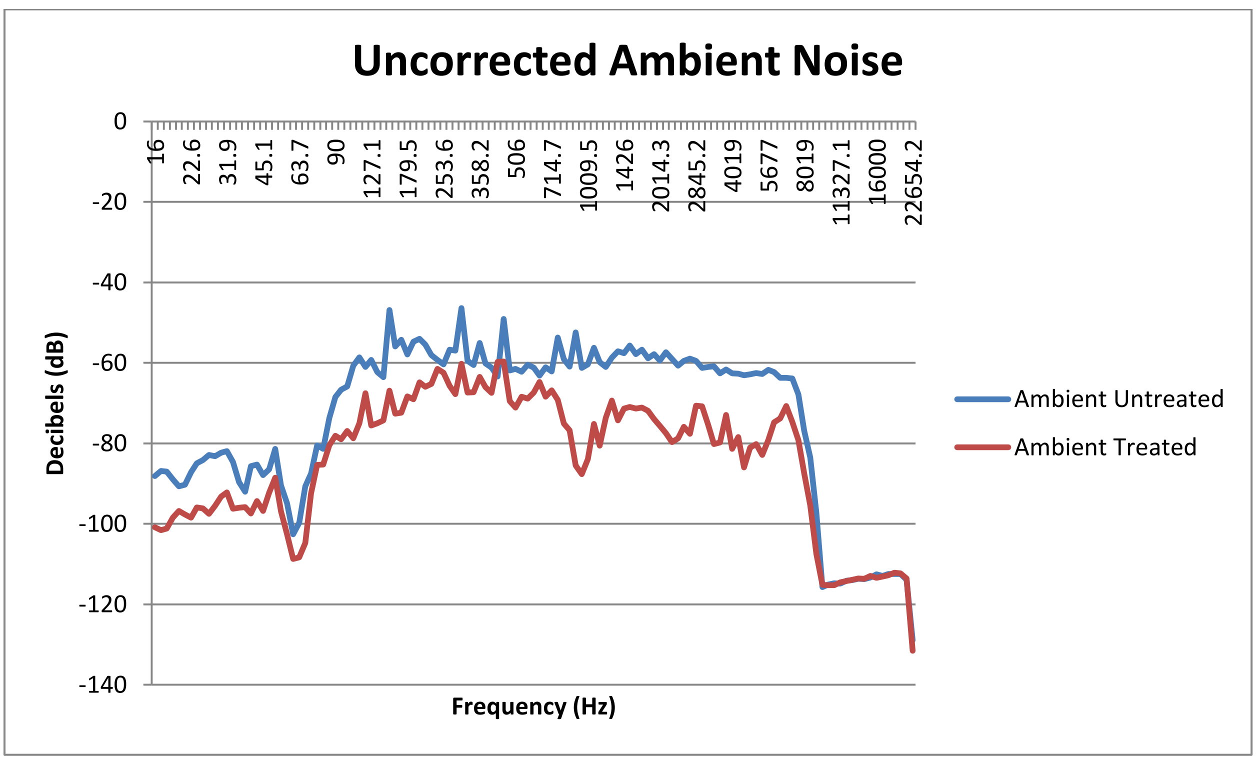


Figure 47: Uncorrected Ambient Noise

The spectral measurements provide useful insight into the results of the A-weighted SPL tests and quantify the performance of the acoustic foam.

Acoustic Performance

In present form, the treated Stage 3 DRI is slightly better than an untreated Stage 3 DRI. At this time the best full-power measurement is 7dB over the 65dBa specification, based on the A-weighted measurements described above. It is believed that the failing lies with the test set up and not with the unit itself. The treated unit was tested inside the PPS production facility, an acoustically “dirty” test space that included the noise of normal business operations, peripheral test equipment, large power supplies, and other solar inverters. A correction was made for some of this extraneous noise by subtracting out the ambient measurement from the full power measurement, but the noise of the accompanying test equipment remains.

Regardless, the effects of the acoustic treatments can be seen plainly in the treated graph. The graphs of treated and untreated units display vastly different concentrations of acoustic energy. The graphs have a very different shape. In the graph for the treated unit, the valleys in the 500Hz to 1000Hz range and in the 2000Hz to 5000Hz range reveal an attenuation of energy that is not present in the graph for the untreated unit. Furthermore, the peak at 6400Hz, caused by the switch components, is of considerably lower height than that in the graph for the untreated unit. This suggests that the acoustic treatments do indeed reduce audible noise in the range where most of the acoustic energy is concentrated.

While the Stage 3 design is much improved over the Stage 2 design, with a 10-13 dB reduction in acoustic noise at full power, more accurate testing will be needed in order to determine whether other sound-reducing modifications will be needed.

7.3.3. 102: CRL Component Verification Testing

The CRL transformer underwent a major redesign to improve thermal performance during Stage 3. The design has just been completed, and is to undergo substantial testing, similar to Stage 2. The tests are:

- Dielectric test
  - Apply AC and DC per UL1741:2010, Section 44 [6] procedure.
- Open circuit/core loss test
  - Measure the voltage and current, and determine instantaneous power loss under expected conditions (nominal excitation voltage and frequency) under a no-load condition.
- Turns ratio test
  - Using standard line voltage (120V/60Hz) applied to the primary, confirm the secondary turns ratio by measuring the ratio of the voltages.
- Short circuit (thermal and impedance) test

    - Bolt the secondary terminals together. Under the nominal excitation method (waveform and frequency), raise the transformer operating voltage until the nominal full load current is drawn.
    - Determine the impedance based upon the applied primary voltage to nominal primary voltage ratio.
    - Keep running the test for 8 hours or until thermal equilibrium is reached in an environmentally controlled chamber and calculate the thermal rise.
- Copper Loss Test – I^2R losses
    - Measure the DC resistance using a micro-ohmmeter and calculate the equivalent AC resistance.

7.4. 200: Control Component Validation Test Results

7.4.1. Overview and Summary of Results

The purpose of these tests was to validate the control system hardware at the PCB level. These tests were identified because the controls hardware underwent a major revision at the end of Stage 2. Each PCB had its own bring-up performed by the board designer, used as an opportunity to profile the performance of the PCB within and up to the design envelope. The following components were tested:

- 1750-0013 Control Board Rev v2.6
- 1750-0041 DRI Peripheral Board v1.0
- 1750-0020 HSADC v1.1
- 1750-0033 GFDI v1.4
- 1750-0015 HMI Assembly

While no formal test data will be presented, the control component validation results were successful and confirmed that the components met performance specifications and complied with their internal interface requirements. A summary of the results follows:

- 1750-0013 Control Board Rev v2.6
    - Main system processor (s) operation confirmed for the purpose of controlling the system.
    - Program memory, storage operation confirmed.
    - Digital bus links confirmed for internal communications.
- 1750-0041 DRI Peripheral Board v1.0
    - External user I/O operation confirmed (Analog/Digital I/O).
    - Bridge triggering capabilities confirmed.
- 1750-0020 HSADC v1.1
    - High speed analog and A/D performance confirmed for the purpose of providing sensor feedback for controls.
- 1750-0033 GFDI v1.4

    - Ground fault detection confirmed with respect to the requirements of UL1741:2010 [6] sections 53-56.
- 1750-0015 HMI Assembly
    - Ability to successfully load Windows CE6 confirmed.
    - Touchscreen interface operation confirmed.

7.5. 300: Subsystem Integration Test Results

7.5.1. Overview and Summary of Results

The main focus of subsystem integration was to combine the new controls hardware with the existing software. The software was modified in one important respect, namely to make the Central Resonant Link (CRL) component optional. The following tests were performed:

- 301: Control subsystem integration
- 302: Communications subsystem integration
- 303: Software review
- 304: System bring-up

No formal test data will be presented for tests 301-304, which on the whole are stages in the project for debugging and bring-up of the system. However, the overall success of this batch of tests can be confirmed by the success of the units' operation and performance during the FAT.

7.6. 400: First Article Test

7.6.1. Overview

Units 1 and 2 were used to extensively confirm all aspects of operation to meet or exceed the system and subsystem specifications. Presently, the 430 series of functional tests have been performed with satisfactory results. Also, sections 410 and 420 have been performed to the extent that the risk of a failure resulting from incorrect fault protection or an inability to control the unit via the main touchscreen or Ethernet interfaces has been mitigated.

The tests that shall be performed are as follows:

- 410: Fault Protection
  Confirm that the software will offer protection against external power conditions and detect abnormal internal conditions such as software failure. This includes:
    - Power faults for each port (over/under-voltage, overcurrent, overload)
    - IEEE 1547.1 [8] Functionality (Abnormal voltage and frequency, anti-islanding detection)
    - System and software faults
- 420: User Interface
  Confirm that each user interface correctly and reliably communicates and conforms to any security/restriction policy, including passwords and local lock-out of other interfaces.
    - Ethernet
    - Modbus-master
    - Modbus-slave
    - Front panel controls (touchscreen)

- 430: Functionality
  Confirm that each mode operates correctly and measure power quality while doing so. This includes:
    - Distributed Generation (DG) Mode
    - Demand Response (DR) Mode
    - Standalone (SA) Mode

  Perform detailed assessment of the following control algorithms:
    - MPPT steady state and dynamic performance
    - Load port transient response and load shedding behavior
    - Battery charging and discharging profile
- 440: Continuous Operation
  Prove performance over an extended period so that longer term operation is confirmed, using the actual PV array, as well as a battery, resistive load bank, and grid connection.
- 450: Environmental
    - Steady State operation at minimum and maximum operating temperature, tested officially under UL1741 [6] Section 43 and IEEE1547.1 [10>8] Section 5.1.
    - Steady state operation at 95%RH non-condensing humidity
    - UV (ASTM G155) [9] exposure of enclosure and exposed components
    - Rain and sprinkler test pre-compliance, tested officially under UL1741 Section 61
    - Acoustic evaluation using octave and dBA slow measurements on class 1 meter to confirm noise level equal or better than 65 dBA@ 1m (SPL)
- 460: Reliability
    - System operation in an environmentally controlled chamber at maximum temperature and humidity.
    - Subsystem level analysis of hotspot temperatures and operational electrical measurements will, in conjunction with the MTBF analysis, identify components for additional testing. Controls components will likely be the focus of this additional testing. The subsystem tests will have thermal cycling at maximum humidity, and operational confirmation at each endpoint's extremities (per MIL-HDBK 217 [10]).

7.6.2. 430: Functional Testing

7.6.2.1. Overview

Functional testing begins by testing the functionality that is independent of the other ports. Because the same functionality was effectively offered during Stage 2, these tests were not performed again. These tests tend to focus on the correct operation of control algorithms which affect the output of the port (as opposed to system level "state control" algorithms). The results from Stage 2 are included for completeness.

- 431 PV Port
    - MPPT Voltage accuracy
    - MPPT Power accuracy
- 432 Battery Port
    - Charging and discharging profile with VRLA Batteries
- 433 Load Port

    - Smart load shedding algorithm
    - Critical load support
    - Power quality
- 434 Grid Port
    - Power quality
    - Active power control
    - Reactive power control
    - PF power control

Following the evaluation of each port's control algorithm performance, the system is tested as a whole. These modes were demonstrated during the product demonstration (Section 7.9). Some additional testing was also performed and is documented here.

- 435 Distributed Generation Mode
- 436 Demand Response Mode
- 437 Standalone Mode

Finally, when the CRL has undergone test 102 to validate the transformer, the system performance impact of the CRL will be evaluated:

- 438 System Functional tests with the CRL

7.6.2.2. Test Setup

All of the above testing was performed in a single test bed designed to provide the DRI with representative sources and loads (Figure 48). Not all of these sources and loads were engaged at the same time, and each test refers to the subset of the test bay that was used. Table 5 details the test and measurement equipment. Figure 49 and Figure 50 show the DRI unit during testing and the test setup, respectively.

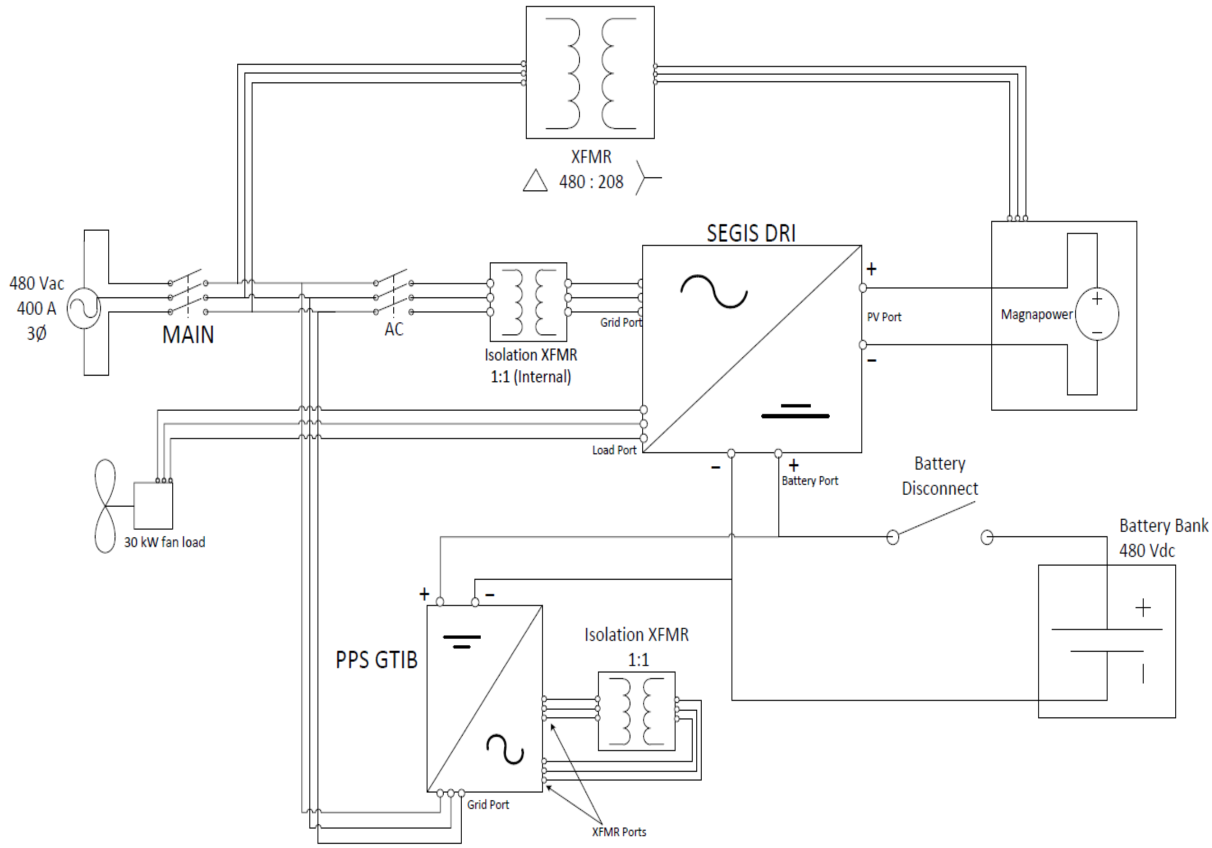


Figure 48: Test Bay Schematic

Table 5: Test and Measurement Equipment

Item	Characteristics	Manufacturer	Model	Qty
Power Analyzer	2 x 3φ 480V and 2 x 600VDC	Yokogawa	WT3000 WT1600	2
Current clamp	600A	Fluke	i80s	3
Current clamp	DC-100kHz, 600 Apk	Danfyzik	751574	6
Digital Oscilloscope	100MHz, 4 Ch	Agilent	6014A	3
Voltage Probe	± 7kV differential isolated	Probemaster	4241A	4
Current probe	100 A/V burden	Fluke	i80s	2
Logic Analyzer	Standard PPS	Tektronix	TLA614	1
Thermal Logger	40 Chan datalogger	Agilent	34970A	1
Thermocouples	Type K	Omega	Any	40
Airflow meter	Hotwire anemometer	Extech	407119A	1
Sound meter	Type 2, Octave resolution with dBA	Extech		1

Figure 49: DRI Unit #1 Undergoing Test

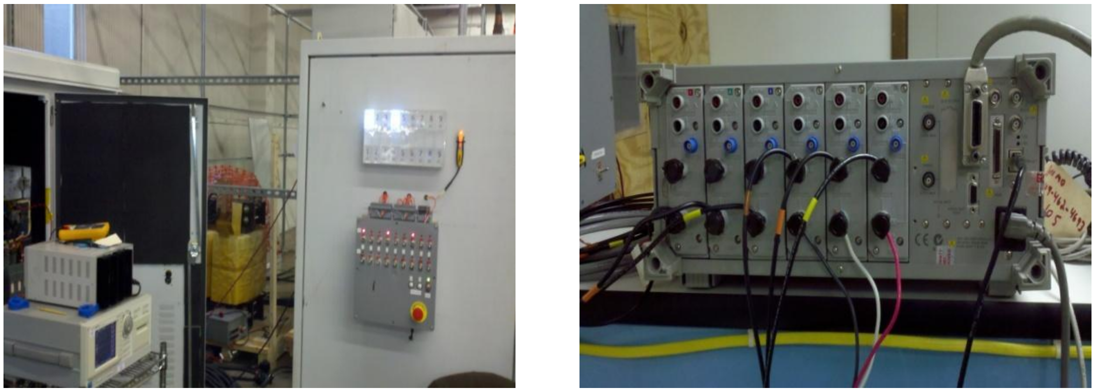


Figure 50: Test Setup with Distribution Box (left) and Power Analyzer (right)

7.6.3. 431: PV Port

7.6.3.1. Overview

The PV port performance was evaluated during Stage 2 (Table 6). One test proposed in the Stage 2 report, and which still remains to be performed, is the set of static and dynamic efficiency MPPT tests from the SANDIA Inverter Performance Test Protocol (2004) [11], sections 5.6.1 and 5.6.2, respectively. The power quality test from Stage 2 is repeated here for completeness.

7.6.3.2. Power Quality Test (Stage 2)

Setup

- Batteries to be charged in DG mode using a PV input with grid connection
- Available PV up to 40kW, using inline series resistance as simulated solar source
- VRLA gel batteries that are not fully charged, in 103Ah, 240Series, 1 Parallel cell configuration (480Vdc nominal), such that they are at float charging stage

Results

Low power operation is demonstrated and the batteries are charged at float voltage and excess power is transferred to the grid port. At the highest power level, 38.1kW/40kW, approximately 95.3% power transfer efficiency was obtained.

Table 6: PV Port Power Quality Test (Stage 2)

Test	Mode	Specification		DE Mode	
	Nominal Power	Min	Max	Test 1 - 3-port DE PV at 40kW	Test 1a - 3-port DE PV at 20kW
Date time				4/28/2010 9:52	4/28/2010 9:57
Available PV	Rectifier Voltage			636.00	648.00
	Resistor drop			275.44	290.58
	Resistor Power			29.09	16.25
	Voltage accuracy			86.62	89.69
	Power accuracy			76.27	81.17
	Resistor load			2.61	5.20
Battery Power	Voltage Vdc	330	600	504.03	504.25
	Current Adc	0	300	-8.72	-7.24
	Power kW	0	100	-4.40	-3.65
PV Power	Voltage Vdc	330	600	360.56	357.42
	Current Adc			105.60	55.92
	Power kW	0	100	38.14	20.02
Grid Power (RMS)	Hz	57	61.5	60.01	60.02
	PF	1	1	0.99	0.99
	kW	0	100	31.69	14.77
	kVA	0	100	31.86	14.94
	V	432	528	493.73	493.20
	I	0	120	37.25	17.49
	ITHD		2	10.51	15.86
	VTHD			2.01	1.46
	Ifund			37.04	493.13
	Vfund			493.58	17.26
Spot Efficiency	Input (kW)			33.74	16.37
	Output (kW)			31.69	14.77
	Efficiency (%)	97	97.5	93.93	90.27

7.6.4. 432: Battery Port

7.6.4.1. Overview

The battery port was tested in Stage 2 using Valve Regulated Lead Acid (VRLA) batteries. Stage 3 field demonstration (see section 7.6.7.2 700700: Field Demonstration) also saw the pairing of the DRI with a Lithium-Ion battery bank. Because the Lithium-Ion batteries require extensive cell-by-cell regulation and monitoring, a battery management system is provided by the vendor (International Battery). The DRI communicates with this system to provide and consume necessary system information.

The battery charging profile is a three-stage algorithm that defines a bulk voltage, float voltage, and bulk-to-float transition current. This algorithm has been thoroughly tested in PPS's products for lead acid batteries. One concern for applying the algorithms to Lithium Ion batteries was the voltage ripple, so this was the emphasis of Stage 3 testing.

7.6.4.2. Power Quality

The test setup used the general setup described in section 7.6.2 430: Functional Testing. VRLA batteries were used, as this test required passing results as a prerequisite for moving to the Lithium-Ion battery bank. The test was a success, with results showing the important figure of < 2% DC voltage ripple (Table 7).

Table 7: Battery Port Power Quality Test

Test	Mode	Specification		Battery Discharging			Battery Charging		
	Nominal Power			100	100	80	-100	-100	-80
	Nominal Voltage	Min	Max	580	450	300	580	450	300
Battery Power	Voltage Vdc	330	600	507.33	460.16	305.41	518.13	443.19	310.91
	Current Adc	0	300	209.23	231.63	281.38	184.97	215.34	258.94
	Power kW	0	100	106.43	106.62	85.96	-95.87	-95.46	-80.39
	Voltage Vac (ripple RMS)			7.76	7.41	6.03	7.88	7.27	6.12
	Current Iac (ripple RMS)			6.45	6.59	7.15	5.79	6.39	6.75
	V ripple %		2	1.5%	1.6%	2.0%	1.5%	1.6%	2.0%
	I ripple %			3.1%	2.8%	2.5%	3.1%	3.0%	2.6%
Grid Power (RMS)	kW	0	100	100.8	100.6	80.7	-97.9	-98.2	-82.8
	kVA	0	100	101.9	101.9	81.6	99	99.5	83.8
	PF	1	1	0.99	0.99	0.99	-0.99	-0.99	-0.99
	DPF	1	1	0.99	0.99	0.99	-0.99	-0.99	-0.99
	V	432	528	477	474.5	475	464	463	467
	I	0	120	124	125	98.6	123	123.5	103
	ITHD		2	1	0.9	0.9	1.3	1.3	1.3
Efficiency	Efficiency (%)	97	97.5	94.7%	94.4%	93.9%	97.9%	97.2%	97.1%

7.6.5. 433: Load Port

7.6.5.1. Overview

The smart load functionality has not changed since Stage 2, and hence the results are still considered to be valid. The Stage 2 test focused on the successful functioning of the load shedding algorithm, which tries to optimize the load port load given both the available system power and the obligation in DR mode to output a specific quantity of power into the grid. These results have been included in this report for completeness.

7.6.5.2. Smart Load Functionality Test

Setup

- System is in Distributed Energy mode
- Battery is charged
- Available PV power is changed every 5 seconds to 20kW, 30kW, 40kW, 20kW, 0kW
- The following loads are connected:
  - .1. Contactor 1: 10kW – Priority 1
  - .2. Contactor 4: 5kW – Priority 2
  - .3. Contactor 5: 4 light bulbs – Priority 3

Result

- When available power is 20kW no contactors are turned on
- When available power is 30kW contactor 1(10kW) turns on
- When available power is 40kW contactors 4(5kW) and 5(light bulbs) turn on 1 second apart
- When available power is 20kW contactors 5, 4 and 1 turned off 1 second apart

The data in Figure 51 is taken from the system serial output. It shows basic running parameters on all ports and, in particular, the available PV power is highlighted orange across the step change. The five contactor statuses are highlighted in pink across the transition.

Serial Data during load shedding/ Connection															
Date and Time	507164036	507164037	507164039	507164040	507164041	507164042	507164043	507164045	507164046	507164047	507164048	507164049	507164051	507164052	507164053
Time	16:40:36	16:40:37	16:40:39	16:40:40	16:40:41	16:40:42	16:40:43	16:40:45	16:40:46	16:40:47	16:40:48	16:40:49	16:40:51	16:40:52	16:40:53
Battery Voltage	499	499	500	500	501	500	499	498	499	498	500	500	500	500	498
Battery Current	-11	-12	-8	-9	-8	-9	-11	-11	-10	-11	-8	-10	-6	-7	-11
Battery Power	-5.6	-5.7	-4.1	-4.1	-4.1	-4.4	-5.8	-5.1	-5.3	-5	-4.2	-5.1	-2.8	-3.6	-5
Secondary DC Bus Volta	819	817	823	822	820	814	815	816	823	821	821	817	815	819	817
Battery Temperature	25.6	26.8	25.7	26.2	26.6	26	25.5	26.7	26.2	26.8	26.8	26.2	25	26.1	26.4
Grid Voltage(AB)	491	491	490	489	489	489	490	489	489	489	489	489	489	491	491
Grid Current	36	41	41	38	33	33	41	41	41	37	33	33	30	38	38
Grid Real Power	13	21.6	10.8	10	10	10.7	19.4	14.8	13.9	13.2	-3.7	-3.1	2.7	13.6	13.4
Grid Reactive Power	0	-0.2	0.2	0.1	-0.1	-0.3	-0.3	0.3	0.2	-0.1	-0.3	-0.1	-0.1	-0.1	-0.2
Grid Temperature	34	33.7	33.7	33.8	33.6	32.5	34.1	32.4	33.9	35.5	32.7	33.5	33.5	35.1	33.7
PV Voltage	348	352	352	352	352	348	353	357	355	350	342	342	341	344	342
PV Current	55	80	79	79	79	80	102	100	101	103	54	56	56	56	56
PV Power	19.2	28.1	27.7	27.7	27.8	27.8	35.9	35.7	35.8	35.9	18.5	19	19.1	19.2	19.2
PV Temperature	33	31.8	32.8	33.9	32.3	32.8	31.9	31.9	34.3	33.7	32.7	35.1	33.9	33.1	33.5
SPL Voltage(AB)	1	1	481	481	478	481	481	478	479	483	479	479	482	-3	1
SPL Current	0	0	36	33	35	35	37	35	35	34	35	34	32	1	0
SPL Power	0	0	30.1	27.5	29.1	29	30.4	29.2	29.3	28	29	28.4	26.3	0	0
SPL Temperature	25.1	25	25.3	25.9	25.3	25.7	25.9	26.2	25.8	26.1	26.6	26.6	26.9	26.8	26.6
Contactor 1 Status	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0
Contactor 2 Status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Contactor 3 Status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Contactor 4 Status	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0
Contactor 5 Status	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
# of connected Loads	0	0	1	1	1	1	1	2	3	3	3	2	1	0	0

(pink)	Load Status changed
(orange)	PV Power changed

Figure 51: Load Port Test Results

7.6.5.3. Smart Load Transient Test

During the Smart Load Functionality Test data was also taken looking at the waveforms during transients. The scope capture in Figure 52 shows the overall profile of the output current waveform (green) and the DC bus voltage (yellow), followed by details of each transition. Note the following:

- Voltage is generated before the contactor closes, such that a random phase angle is applied to the load
- The output capacitor can be seen discharging as the final load is disconnected
- The load transitions are smooth between applied loads

Figure 53 shows the details of test transitions.

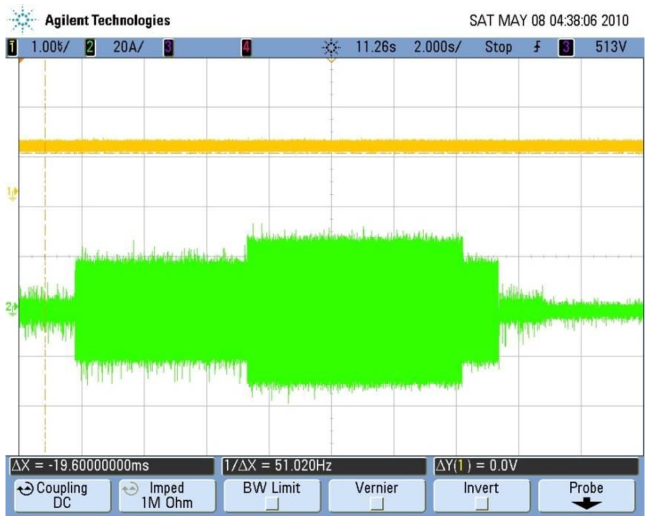


Figure 52 : Transition Test, Overall Profile, Showing 4 Distinct Transitions Over 16 Seconds.

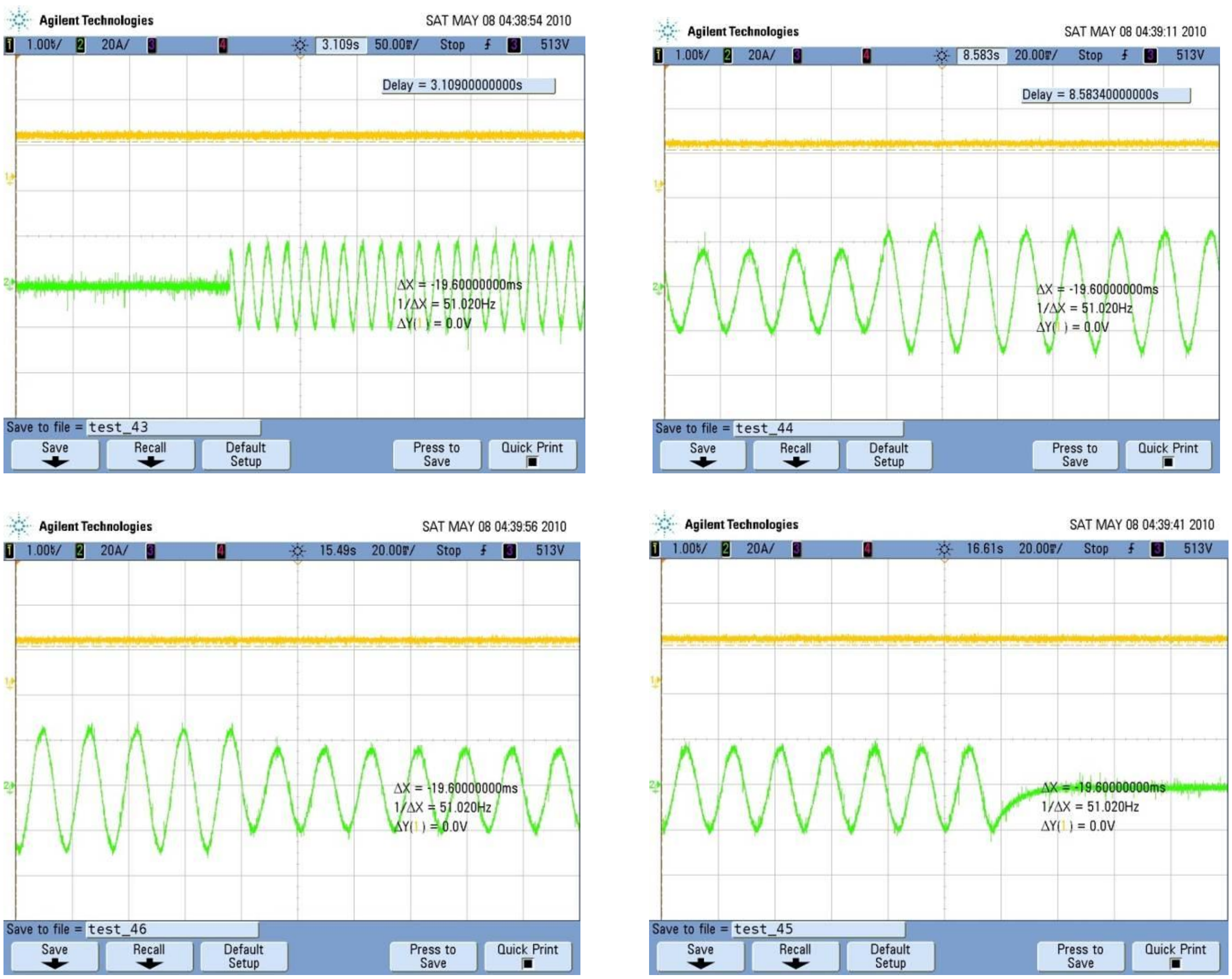


Figure 53: Details of Each Test Transition, Chronologically Ordered From Top Left.

7.6.6. 434: Grid Port

7.6.6.1. Overview

The grid port performance was evaluated in Stage 2 for power quality, efficiency and compliance to the electrical specification. These results are included for completeness. During the Stage 2 demonstration, a combined command was requested by SNL and developed ad-hoc. This was then successfully demonstrated at 0.85 PF, 100kW. For Stage 3, this function was incorporated into Demand Response (DR) Mode. It was required to be evaluated for accuracy over a range of conditions. The main test remaining for the grid port was then to confirm the accuracy of the combined command. Efficiency was also measured for the grid-battery port during this test, which confirmed the general validity of the Stage 2 results.

7.6.6.2. Power Quality Test

The power quality measurements were taken during Stage 2 under the following conditions:

PF Mode

- System is in Power Factor correction mode
- PV is supplying 40kW, with the battery connected but not being used
- The system kVAR command is used to control the reactive power sent to the grid

The PF mode results are shown in Table 8.

Combined Mode

- Battery port providing 100kW power
- Grid port outputting power at requested power factor

The combined mode results are shown in Table 9.

Table 8 : Power Quality Measurements from Stage 2. The System Has a Purely Reactive Power Command (PF mode)

Test	Mode Nominal Power	Specification Min	Max	PF Mode Test 6 - 3-port PF +50kVar PV at 40kW	Test 6b – 3-port PF -100kVar PV at 40kW
Date Time				4/28/2010 10:49	4/28/2010 11:16
Available PV	Rectifier Voltage			686	687.00
	Resistor drop			18.46	4.78
	Resistor Power			0.13	0.01
	Voltage accuracy			5.38	1.39
	Power accuracy			2.75	0.69
	Resistor load			2.70	2.50
Battery Power	Voltage Vdc	330	600	474.077	476.52
	Current Adc	0	300	-2.197	-2.00
	Power kW	0	100	-1.043	-0.96
PV Power	Voltage Vdc	330	600	667.538	682.22
	Current Adc			6.837	1.91
	Power kW	0	100	4.591	1.33
Grid Power (RMS)	Hz	57	61.5	60.016	60.04
	PF	1	1	0.052	-0.04
	kW	0	100	2.64	-3.10
	kVA	0	100	52.045	87.19
	V	432	528	502.075	474.40
	I	0	120	59.848	106.11
	ITHD		2	8.062	3.46
	VTHD			2.16	1.97
	Ifund			59.623	106.03
	Vfund			501.921	474.29
Spot Efficiency	Input (kW)			3.548	0.37
	Output (kW)			2.64	-3.10
	Efficiency (%)	97	97.5		

Table 9 : Combined Command Power Quality Data From Stage 2

Test	Mode	Specification		Power Factor Demonstration	
	Nominal Power	**Min**	**Max**	Test 1 - 95kW + 31 kVar	Test 2 - 95kW -31 kVar
Date time				4/29/2010 11:11	4/29/2010 11:22
Battery Power	Voltage Vdc	330	600	463.50	460.29
	Current Adc	0	300	222.58	226.66
	Power kW	0	100	103174.00	104335.00
Grid Power (RMS)	Hz	57	61.5	60.01	60.01
	PF	1	1	0.95	0.95
	kW	0	100	99646.20	99967.50
	kVA	0	100	104547.20	105587.60
	V	432	528	504.96	491.56
	I	0	120	119.54	124.01
	ITHD		2	2.16	2.72
	VTHD			1.82	1.59
	Ifund			119.95	124.45
	Vfund			504.48	491.33
Spot Efficiency	Input (kW)			103174.00	104335.00
	Output (kW)			99646.20	99967.50
	Efficiency (%)	97	97.5	96.58	95.81

7.6.6.3. Combined command accuracy

Following the development of the combined command in Stage 3, its performance was profiled (Table 10). The test setup was as follows:

- Battery and grid port operating
- Command given for active/reactive power output

Table 10: Combined Command Accuracy

Direction	Battery DC (Vdc)	Real Power (kW)	Reactive Power Command (kVAR)	Actual Reactive Power (kVAR)
Battery to Grid	500	10	0	-2.4
			10	11.6
			50	50.6
			100	99.5
			-10	-10.7
			-50	-49.7
			-100	-84.5
		50	0	-7.9
			10	11.1
			50	50.4
			100	
			-10	11.8
			-50	52.8
			-100	
		100	0	-13.5
			10	10.4
			50	
			100	
			-10	16.8
			-50	
			-100	
Grid to Battery		-10	N/A	0.7
		-50	N/A	9.0
		-100	N/A	12.5
Battery to Grid	450	10	N/A	-2.0
		50	N/A	-6.7
		100	N/A	-14.7
Grid to Battery		-10	N/A	1.9
		-50	N/A	6.2
		-100	N/A	14.4
Battery to Grid	300	10	N/A	-2.4
		50	N/A	-6.9
		100	N/A	-10.0
Grid to Battery		-10	N/A	0.7
		-50	N/A	6.1
		-100	N/A	10.4

7.6.6.4. Efficiency Measurement

Efficiency measurements are given in Table 11.

Table 11 : Efficiency During Battery Charging and Discharging

Direction	Battery DC (Vdc)	Actual Power Out (kW)	Actual Power In (kW)	Efficiency (%)
Battery to Grid	500	9.9	11.47	86.3
		11.8	12.80	92.2
		12.1	17.94	67.4
		15.7	17.37	90.4
		10.8	12.51	86.3
		10.6	13.30	79.7
		10.0	13.99	71.5
		50.2	53.34	94.1
		52.6	55.36	95.0
		51.1	53.14	96.2
		49.6	52.66	94.2
		49.2	53.26	92.4
		100.8	106.43	94.7
		104.0	109.71	94.8
		100.3	106.23	94.4
Grid to Battery		-8.51	-11.6	73.4
		-55.12	-57.1	96.5
		-95.87	-97.9	97.9
Battery to Grid	450	10.0	11.54	86.7
		50.4	53.21	94.7
		100.6	106.62	94.4
Grid to Battery		-10.16	-11.1	91.5
		-50.10	-51.6	97.1
		-95.46	-98.2	97.2
Battery to Grid	300	9.9	11.31	87.5
		50.4	53.57	94.1
		80.7	85.96	93.9
Grid to Battery		-10.47	-10.9	96.1
		-49.58	-51.1	97.0
		-80.39	-82.8	97.1

7.6.7. 435: Distributed Generation (DG) Mode

7.6.7.1. Overview

DG Mode uses PV power as an input and exports it to the grid port, minus any load requirements. The power is maximized using a proprietary MPPT algorithm. To test the algorithm, two main tests can be performed:

1) A controlled environment test, where the power and voltage can be accurately assessed under both steady state and dynamic conditions. This will be performed according to the Sandia Inverter Performance Test protocol (2004) [11] (see section 7.6.3, 431: PV Port for more details).
2) A field test, where the DRI is attached to a live PV array and its performance is monitored over a long time period. This test is currently ongoing, but initial data suggests a peak of 94.1% efficiency observed at 72kW output (see Table 12). Given the operating point (72kW vs. 100kW) and the fact that PE losses leave approximately 97% efficiency, the results suggests an algorithm efficiency of about 97%, a reasonable indication of success.

7.6.7.2. Field test

The DRI is operating in the PV field on one of the two solar arrays (see section 7.9.2, Field Demonstration). The results are preliminary, but as mentioned above, indicate 97% algorithm efficiency.

Table 12: Sample Test Data Taken While Operating in DG Mode over 8 Hrs.

	Date	10/5/2011	10/5/2011	10/5/2011	10/5/2011	10/5/2011
	Time	10:16:39	11:31:04	14:12:24	17:00:03	17:40:06
PV Power	Voltage Vdc	396.1	383.5	364.8	388.6	383.4
	Current Adc	107.0	166.4	211.8	82.2	28.6
	Power kW	42.4	63.8	77.3	31.9	11.0
Grid Power (RMS)	Hz	59.99	60.01	60.01	60.00	59.99
	PF	0.984	0.988	0.989	0.973	0.852
	kW	39.7	60.1	72.7	29.6	9.2
	kVA	40.4	60.8	73.5	30.4	10.8
	V	490.7	495.7	497.8	497.9	498.3
	I	47.4	70.8	85.3	35.2	12.4
	ITHD	7.03	6.45	5.63	11.04	31.65
	VTHD	1.43	1.66	1.71	1.90	1.86
	Ifund	47.3	70.7	85.2	35.0	11.8
	Vfund	490.6	495.6	497.7	497.8	498.3
Spot Efficiency	Input (kW)	42.4	63.8	77.3	31.9	11.0
	Output (kW)	39.7	60.1	72.7	29.6	9.2
	Efficiency (%)	93.7	94.1	94.1	92.7	84.1

7.6.8. 436: Demand Response (DR) Mode

7.6.8.1. Overview

The DR mode was evaluated in Stage 2 to confirm that the unit had good agreement between the requested grid power and the actual output; it was also tested for the functional case when operating a critical load that was close to or exceeded the available power. In this case, the critical load should be serviced first.

7.6.8.2. Critical load priority

Setup

- System is in Demand Response mode
- PV simulator outputs 40kW
- Grid port command is set to 100kW
- Load port has 100kW critical load attached

Results

Table 13 shows power quality data taken from the PQA. Because the load port has a critical load attached, it will take priority above the grid command, even though it is 100kW. In addition to the functionality, we see the performance of the grid port when no load is attached, notably that the power quality is dominated by the 15kVAR of filter capacitance. Note also the system efficiency of 95.75% with all 4 bridges running when the CRL is not installed.

Table 13 : DR Mode Power Quality

Test	Mode Nominal Power	Specification Min	Max	DR mode Test 4 - four-port 40kW PV 100kW load, grid 100kW cmd
Date time				5/7/2010 12:45
PV Power	Voltage Vdc	330	600	355.98
	Current Adc	0	300	106.14
	Power kW	0	100	37824.00
Battery Power	Voltage Vdc	330	600	385.86
	Current Adc			187.03
	Power kW	0	100	72175.00
Load Power (RMS)	V	432	528	481.19
	I	0	120	123.53
	P (kW)	0	100	102956.00
	S (kVA)	0	112	103032.00
	Q (kVAR)	0	100	-3952.00
	PF	0.95	1	1.00
	Fu (Hz)	57	61.5	60.00
	ITHD		2	0.60
	VTHD			3.74
Grid Power (RMS)	V	432	528	489.98
	I	0	120	14.98
	P (kW)	0	100	2363.00
	S (kVA)	0	112	12712.00
	Q (kVAR)	0	100	14694.00
	PF	0.95	1	0.19
	Fu (Hz)	57	61.5	60.00
	ITHD			98.42
	VTHD		2	3.16
Spot Efficiency	Input (W)			109999.00
	Output (W)			105319.00
	Efficiency (%)	96.5	97.5	95.75

7.6.9. 437: Standalone (SA) Mode

7.6.9.1. Overview

Standalone Mode was tested in Stage 2 and the results are included here for completeness. The main test was to confirm the performance of the system when transitioning between standalone and the other modes, which are all grid connected. The performance is seamless to within the control system resolution (about 6kHz).

7.6.9.2. Transient Analysis

Setup

- System running with 100kW grid command in DR Mode
- Grid port is disconnected via a contactor
- Load port has 100kW resistive load connected

Result

The grid is disconnected as can be seen in Figure 54 from the top capture at -0.25 seconds. The bottom capture shows both voltage and current stability on a cycle by cycle basis.

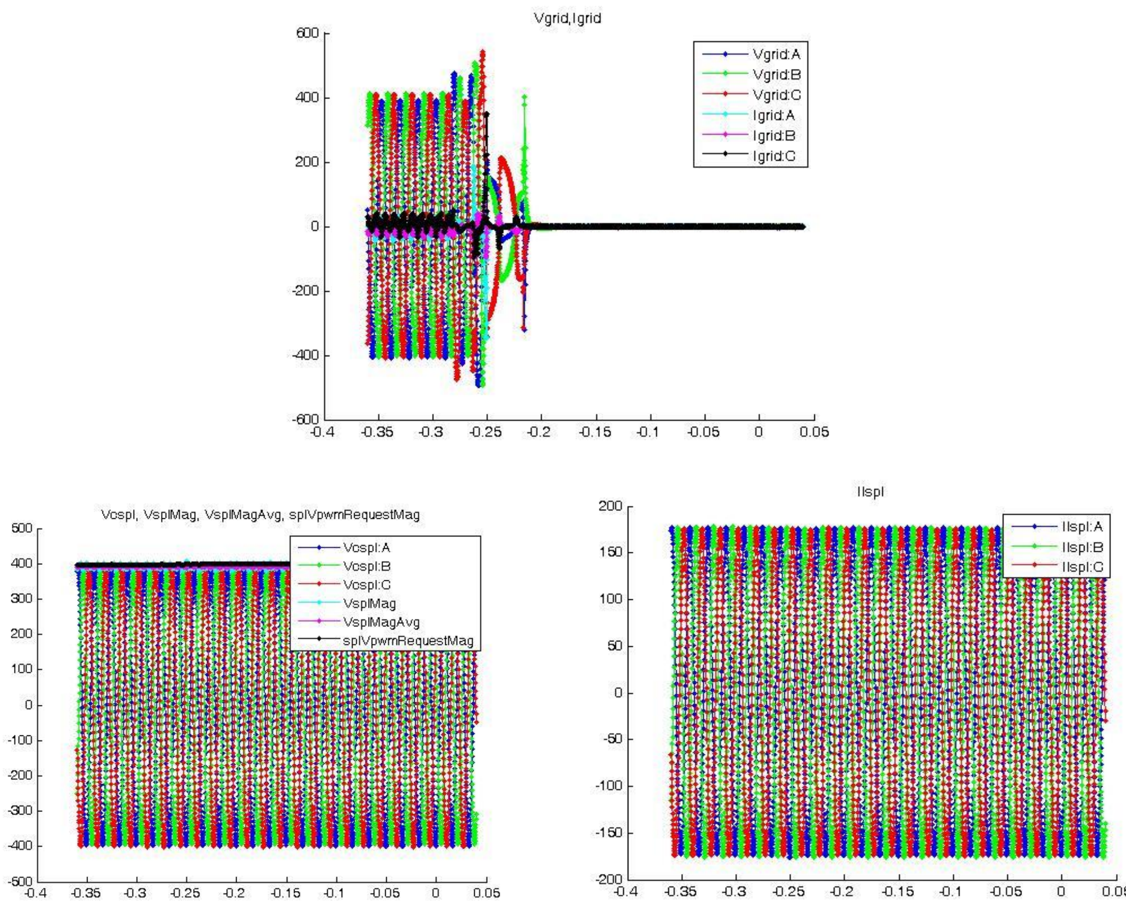


Figure 54: Transient Analysis

7.6.10. 438: System Functional Tests with CRL

7.6.10.1. Overview

When the CRL has been verified at the component level, the following tests will be performed with a system that includes the CRL as an option. The tests are:

- Transient response
  - .1. 0-100kW ramp up time. Performance must equal or exceed that measured during Stage 2, which was 20 cycles.
  - .2. 100 – 0kW ramp down time. Performance must equal or exceed the Stage 2 time measurement of 7 cycles.
- Comparison tests with/without the CRL in place:
  - .1. Grid port power quality
  - .2. System efficiency
  - .3. Acoustic noise

7.7. 500: Compliance Testing

7.7.1. Overview and Summary of Results

The DRI is to undergo full certification to UL1741-2010, [6] which includes evaluation using procedures from the following standards:

- IEEE 1547.1 [7] including
  - o ANSI C37.90.2-2004 IEEE Standard for Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers
  - o ANSI C61.41.2-2002 IEEE recommended practice on characterization of surges in low-voltage (1000 V and less) AC power circuits
  - o ANSI C37.90.1-2002 IEEE Standard for Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus.

In addition, the inverter will be filed with the California Energy Commission (CEC) as a listed inverter, which requires testing to the Sandia Inverter Performance Protocol [11], and also as compliant with the FCC Part 15, as a Class A Unintentional Radiator for industrial environments. This requires testing to ANSI C63.4. [12]

Presently, the following pre-compliance testing has been performed to confirm that the system has a reasonable chance of succeeding UL1741 [6] testing:

- Section 44 Dielectric test
- Sections 53-56 GFDI compliance

7.8. 600: Production Testing

7.8.1. Overview and Summary of Results

All units must undergo a final quality assurance (QA) test before being shipped. Unit 1 was not required to have such a test, as it has undergone much more extensive testing. Units 2 and 3 have undergone testing (Figure 55) and have been used to revise the test procedure to ensure that the final test is relevant and a good indicator that each unit produced will meet the product specification. Subsequent units will undergo the final test following manufacture.

To summarize:

- Unit 1 has been tested and is now undergoing extensive beta testing at the PPS 200kW solar Field.
- Unit 2 and unit 3 have undergone a production test, which was used as an opportunity to develop a time efficient and cost effective procedure for the remaining units.
- Units 4-6 will be tested to the finalized procedure.
- Unit 7 will host some novel design features, and be used to address any failures identified during the preceding tests. It will use the procedure developed above, but will include suitable modifications if necessary.

Figure 55 : SEGIS DRI Units #2 and #3 Undergoing Production Test

7.9. 700: Field Demonstration

7.9.1. Overview

The field demonstration test plan was released to the SEGIS program as part of Task 3a. Demonstration Verification Test Plan including a WBS of the test schedule. It was performed during **Task 7a. Demo Site Conference** on September 29, 2011, at the PPS 200kW solar Field in Princeton, NJ. The demonstration of the DRI's capabilities was by all accounts a success.

The schedule that was performed on the day was:

1. Demonstrate Factory Acceptance Test and Quality Control
   1.1. Show Factory Acceptance Test area, procedure and results from a unit which has recently had Factory Acceptance Test performed.
2. Demonstrate Demand Response Mode
   2.1. Connect load output to resistive load.
   2.2. Show command control over grid output at 25, 50, 75, 100kW.
   2.3. Show 100kW at 0.85 PF leading and lagging.
   2.4. Show ± 50 kVAR and transitions between leading and lagging compensation.
   2.5. When input power is limited, demonstrate action of Smart Load control to turn off non-essential loads.
3. Demonstrate Distributed Generation mode
   3.1. Show maximum power tracking of 100kW PV array using MPPT.
4. Demonstrate Battery Charging
   4.1. Discharge remaining battery power in Demand Response Mode to highlight "best effort" to service grid requests.
5. While charging, monitor performance via the remote interface demonstration (below)
   5.1. Demonstrate ability to respond to PJM control signal
   5.2. Demonstrate ability to control and co-ordinate with a Battery Management System (BMS).

7.9.2. Field Demonstration Site

Figure 56 through Figure 58 show features of the field demonstration site.

Figure 56 : Operator's Station (left) and DRI (right)

Figure 57: The Trailer Used To House the Lithium Ion Battery Bank

Figure 58: 200kW PPS Solar Field, Used for Development of PV Performance

8. MARKET UPDATE

8.1. Target Applications for the DRI

PPS is pleased to have identified potential customers for the 100kW DRI. PPS remains confident that the DRI controller is a promising technology that can provide commercially viable interface for PV system integration into the utility grid. The controls and communication features allow the units to actively communicate with other units and with energy management systems to work in a distributed-generation grid. The SEGIS DRI project has opened many new opportunities for PPS to develop systems similar to the DRI for PV and wind energy integrations, thereby helping the growth of PPS and the growth of green power generation. The DRI will be a fully-commercialized inverter system that reduces the levelized cost of energy (LCOE) of photovoltaic (PV) power by being more efficient, more reliable, and more cost-effective, while also providing valuable grid-support functionality that allows for higher penetration of PV power systems into the electric grid and added value for the system owner and local utility.

8.1.1. PSE&G SEGIS-AC

Our team will demonstrate the DRI with integrated energy storage and grid support controls in areas with high penetration of solar energy that is disrupting the grid. The development effort for this program will be focused on sizing the storage component for the specific demonstration sites, integrating communications with the PSE&G utility operators, demonstrating functions, and analyzing results and economics. PSE&G, the largest electric utility company in New Jersey, has some of the highest penetration rates of solar in the country, and are at the forefront of planning for significant additions of solar and wind.

8.1.2. ACE Program

Atlantic City Electric (ACE) is the second largest public utility in New Jersey and has some of the highest penetration rates of solar in the U.S. As a result of the high penetration of solar, a recent 1.5MW solar installation has been delayed until a 1MW; 1MWh energy storage system is installed as a complement to the system. The project is still in negotiation, but is looking to utilize 10 DRI units and 5 standard GTIB units for solar integration.

8.1.3. Alcatraz

As part of an American Reinvestment and Recovery Act project to renew the roofing on Alcatraz (Figure 59), our team is helping to install an approximately 350kW solar array accompanied by batteries and our advanced power electronics to reduce the Alcatraz's diesel fuel consumption. The solar modules are manufactured by SunPower Corp. (http://us.sunpowercorp.com/), the batteries are manufactured by East Penn (http://www.dekabatteries.com/), and the power conditioning system (inverters and microgrid system controller) is provided by Princeton Power Systems.

Figure 59: Alcatraz Island, San Francisco Bay, California

This system is unique in that it will prioritize the island's energy generation sources in the order of cleanest to dirtiest energy. As such, the island will use energy provided by the solar array first, followed by available energy in the batteries, followed by a diesel generator as the "last resort." In order to make the diesel generator operate more efficiently, the generator will run at 100% capacity and charge the batteries with any excess energy to result in reduce diesel fuel usage. This functionality will be regulated by an external controller that will be provided by Princeton Power Systems. System commissioning is in December 2011. It is expected that diesel fuel usage will be reduced by 30-40%.

8.1.4. Army Micro-grids

PPS supplied two 100kW inverters, one for solar configuration and one for battery configuration (note that the DRI will consolidate the power electronics into one unit), while simultaneously connected to a generator in a microgrid format in order to provide renewable energy to the microgrid and reduce diesel fuel consumption. We succeeded in operating the micro-grid application for the U.S. Army on Fort Irwin (Figure 60). With the concept proven, the system was deployed in the Middle East and is under operation.

Figure 60: Micro-grid in Fort Irwin Operated by Princeton Power Inverters.

8.1.5. Pennsylvania, New Jersey, and Maryland (PJM) Interconnection Services

As PV technologies become more ubiquitous, these systems may impact grid reliability on both the distribution (e.g., voltage fluctuation) and transmission systems (e.g., variability). This may cause utilities to severely limit PV installations or severely increase integration and interconnection costs. PJM is looking for storage technologies to mitigate these issues with advanced functions such as using reactive power storage functions developed consistent with the EPRI Smart Inverter Initiative and utility communication protocols. PJM provides compensation for providing these services, allowing for an additional revenue source for those who partake in the PJM grid ancillary services market.

8.1.6. UPS / Data Centers

There are two (2) types of widely used uninterruptible power supplies (UPS)—double conversion and line interactive. Line interactive systems utilize contactors to switch from grid power (when the grid is down) to backup power to power critical loads. This contactor switch assumes a short lag time between the grid going down and the backup power system starting up. Alternatively, double conversion systems utilize capacitors for a constant ride-through from grid outage to backup power systems start-up. Because the power is constant, double conversion systems are the preferred UPS for data centers world-wide.

Data centers represent a major energy cost for businesses worldwide. In the U.S. alone, data centers accounted for 2% of energy usage in 2010. To date, data centers have been hesitant to adopt renewable energy generation sources to offset energy costs because of their inherent intermittency. With the double-conversion UPS functionality of the DRI, PPS will target a new market segment for solar and storage as a means to offset energy costs for data centers.

8.1.7. Electric Vehicle Charging Infrastructure

The advanced functions of the DRI will allow PPS to compete in a new market that combines the demand for electric vehicles and renewable energy. By 2015, there will be approximately 600,000 private charging stations and approximately 400,000 public charging stations in the United States. These numbers are driven by domestic demand for electric vehicles. Additionally, the demand for renewable energy is increasing. This demand is driven through both federal and state subsidies, consumer interest, and a defined return on investment (ROI) for these systems. While these are promising signs of an emerging market, there is one caveat: the utility grid as is cannot compensate for a systemic increase in both renewables and electric vehicles (EVs). To allow for this infrastructure, utilities will need energy storage to accompany the installation of EV charging stations and renewable energy sources as they become more ubiquitous.

The PPS DRI product represents a solution to this problem. By incorporating two DC ports into one power electronics system, the DRIs allow for both a generation source (PV) and a storage source (batteries) that eliminates grid issues such as demand, VAR variability, frequency regulation, and backup power. PV installers/integrators see this as a potential product that could expand their businesses.

8.2. Marketing Launch and Beta Testing

One of the most visible outreach efforts is a demonstration 200kW PV and energy storage system at 201 Washington Road, Princeton, NJ, on the campus of the Sarnoff Corporation. Construction of the 200kW Solar Array commenced in mid-February and was completed in July 2011. To support the effort, PPS is investing $6.0M alongside the New Jersey Economic Development Authority to complete the demonstration site and build a 20,000+ square-foot manufacturing facility in New Jersey for inverters, DRIs, and systems. The demonstration site will be a continued focus of marketing efforts for the DRI.

8.2.1. Beta Site Testing

Critical to the success of the demonstration is being able to visualize the performance of the DRIs in order to understand how the system operates and allow customers to become familiar with the performance features. For this reason, each of the deployed DRIs will be monitored using the data acquisition and monitoring system that has been developed during the stage II and stage III program. Input and output voltages and currents, various system temperatures, power meter readings, and operational profiles will be recorded. All reported faults or errors will be reported directly back to PPS along with diagnostic data, allowing for any problems in the field to be diagnosed quickly.

8.2.2. Telemetry at Site Demonstration Location

The site at 201 Washington Road Building #2 is a challenging location for Internet service, which is ideal for demonstrating the types of environments where DRI systems may be installed (in remote locations or at the end of distribution lines, where the reliability and security benefits of the DRI are most noticeable).

The best service available at the site is via 3G cellular. With the addition of boosters and directional antennas, the best connection has been achieved, though still not completely reliable. To buffer the reliability issues a local server “Standalone HMI” has been installed to gather and cache performance, fault, and error data. This ability to cache the data ensures a continuous record.

The system comprises a local server running an HMI similar in function and look and feel to the HMI embedded in the DRI front door. The Standalone HMI has parameters for controlling ancillary equipment such as generators or third-party power meters, as well as the ability to set multiple system parameters simultaneously. It records all parameters of all PPS devices attached to it and displays them in real time. This data is uploaded to a Network Operations Center, shown in Figure 61, either in real time or cached and uploaded when Internet service is restored. General Internet service is also provided for testing service engineers and technicians.

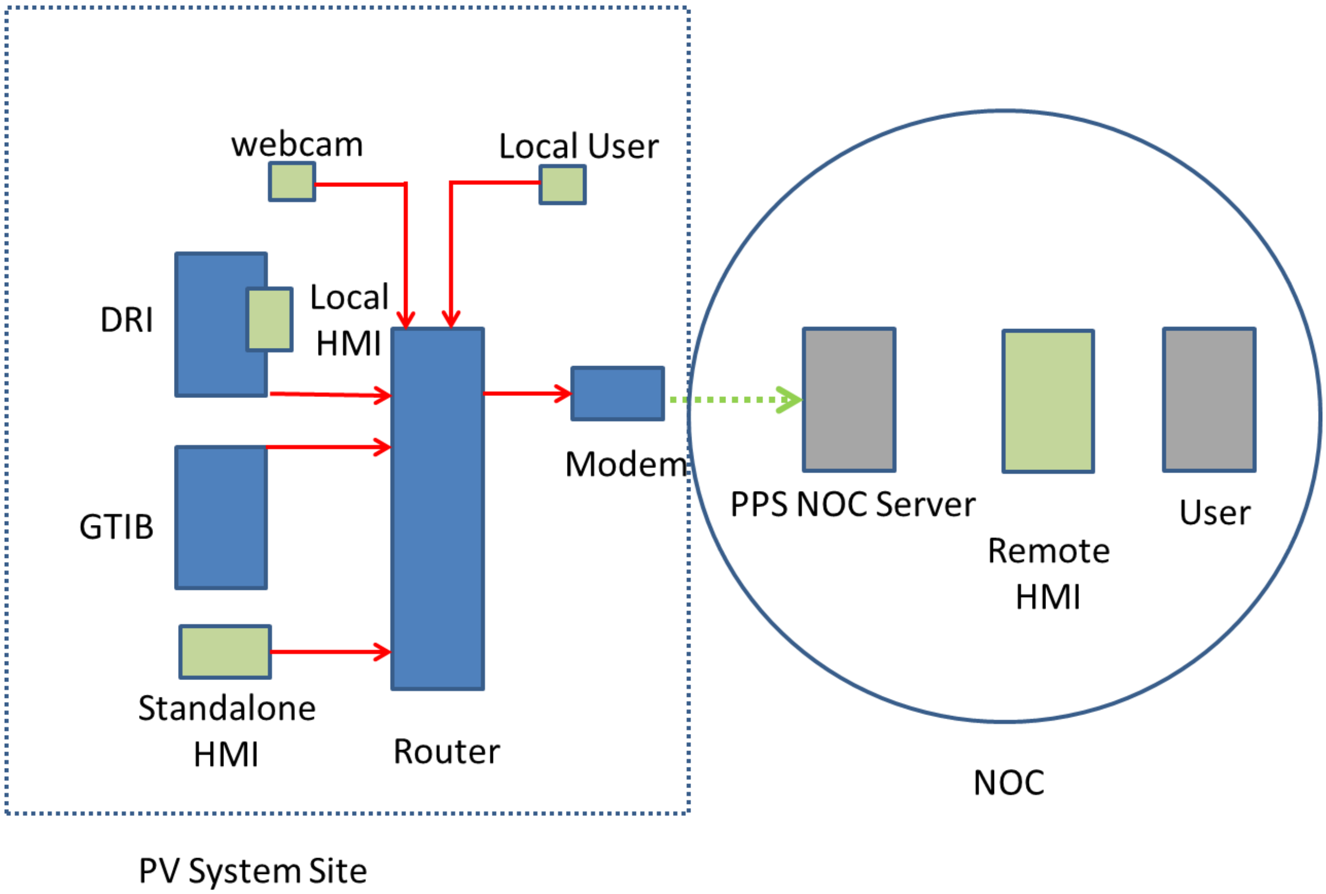


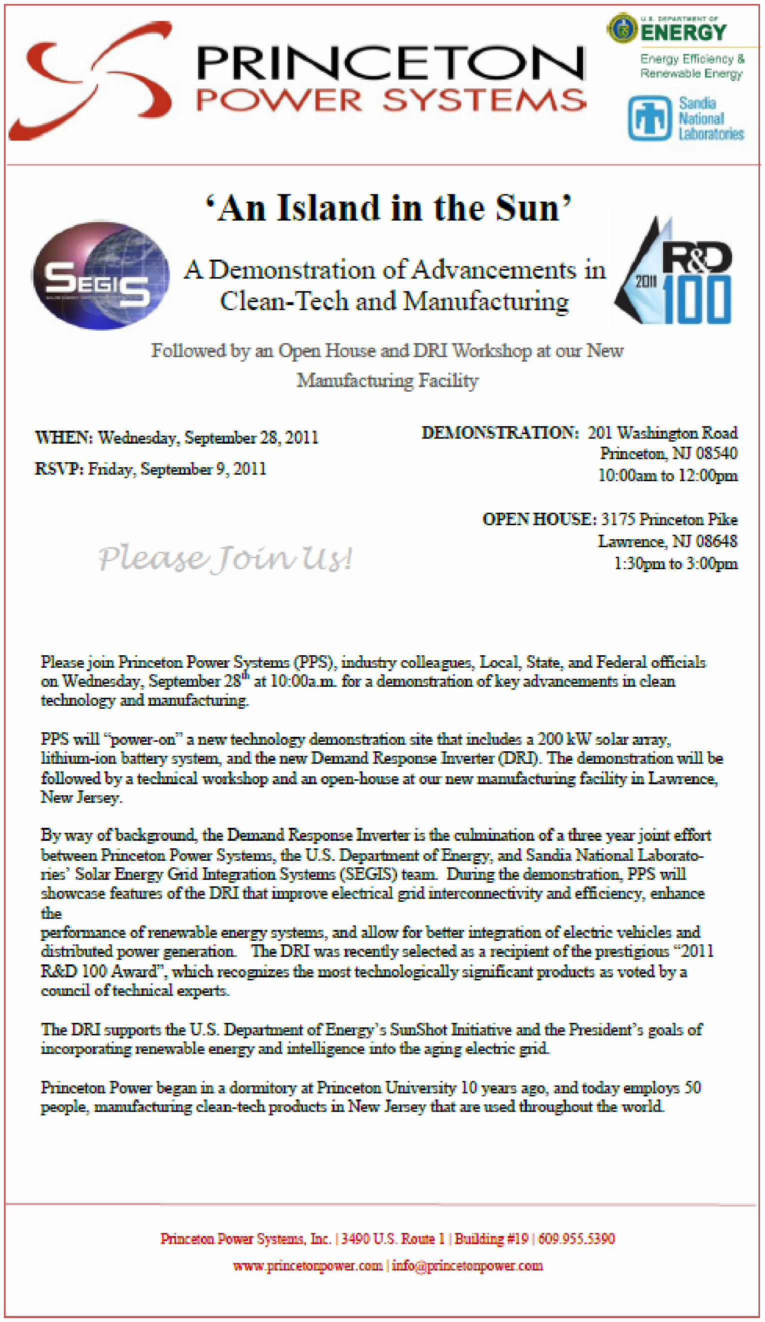
Figure 61: Illustration of the Telemetry for Field-Deployed Systems

8.2.3. Network Operation's Center (NOC)

The Network Operations Center, or NOC, is located at PPS's headquarters in Princeton, NJ. The NOC receives real-time or locally cached parameters from multiple standalone inverters or local HMIs via any type of Internet connection. It provides easily accessible visualization of real-time performance data for a selected inverter or system of inverters. It provides the ability for basic remote troubleshooting of issues and alarms seen in remote systems. It alerts the NOC operator of faults and required maintenance for system service dispatch and scheduling. It provides the ability to remotely control inverters, to upgrade firmware, assist troubleshooting, and fix errors. It provides more sophisticated and user-friendly interpretation of alarms, e.g., "soft alarms" when power output drops below expected levels. The NOC requires data to be reported as close to real time as possible for best performance and reliability.

8.3. Site Demo Conference "An Island in the Sun"

The intent of this Stage 3 "**Demonstration Conference"** was to showcase to utilities, customers, stakeholders, and government officials the new and advanced DRI functionalities, with grid interactivity, new hardware capabilities, innovative application options, and value-added features that make the DRI attractive. The impacts of DRI advancements were presented with use case scenarios presented in relation to the distributed generation problems utilities and stakeholders need to be solving now or in the near future. This conference was also a public demonstration of progress, success, lessons learned, barriers overcome, and future needs as standards and codes catch up to SEGIS advances. The goals of the Demo Conference were technical, educational, and market outreach. The invitation is shown in Figure 62.



PRINCETON POWER SYSTEMS

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

Sandia National Laboratories

'An Island in the Sun'

A Demonstration of Advancements in Clean-Tech and Manufacturing

Followed by an Open House and DRI Workshop at our New Manufacturing Facility

WHEN: Wednesday, September 28, 2011

RSVP: Friday, September 9, 2011

DEMONSTRATION: 201 Washington Road
Princeton, NJ 08540
10:00am to 12:00pm

OPEN HOUSE: 3175 Princeton Pike
Lawrence, NJ 08648
1:30pm to 3:00pm

Please Join Us!

Please join Princeton Power Systems (PPS), industry colleagues, Local, State, and Federal officials on Wednesday, September 28th at 10:00a.m. for a demonstration of key advancements in clean technology and manufacturing.

PPS will "power-on" a new technology demonstration site that includes a 200 kW solar array, lithium-ion battery system, and the new Demand Response Inverter (DRI). The demonstration will be followed by a technical workshop and an open-house at our new manufacturing facility in Lawrence, New Jersey.

By way of background, the Demand Response Inverter is the culmination of a three year joint effort between Princeton Power Systems, the U.S. Department of Energy, and Sandia National Laboratories' Solar Energy Grid Integration Systems (SEGIS) team. During the demonstration, PPS will showcase features of the DRI that improve electrical grid interconnectivity and efficiency, enhance the performance of renewable energy systems, and allow for better integration of electric vehicles and distributed power generation. The DRI was recently selected as a recipient of the prestigious "2011 R&D 100 Award", which recognizes the most technologically significant products as voted by a council of technical experts.

The DRI supports the U.S. Department of Energy's SunShot Initiative and the President's goals of incorporating renewable energy and intelligence into the aging electric grid.

Princeton Power began in a dormitory at Princeton University 10 years ago, and today employs 50 people, manufacturing clean-tech products in New Jersey that are used throughout the world.

Princeton Power Systems, Inc. | 3490 U.S. Route 1 | Building #19 | 609.955.5390
www.princetonpower.com | info@princetonpower.com

Figure 62: Site Demonstration Invitation

8.3.1. Unique and Significant DRI Functions Demonstrated

The following statements show the “Use Case Scenarios” that the PPS Team used to exercise the DRI and attached PV and Energy Storage System during the conference. The conference was unique in that it provided an outdoor environment with a large commercial-scale solar array and energy storage system, to demonstrate real-time performance of the DRI in an actual user environment.

The Use Case Scenarios were:

- Start-up, synchronization, and steady-state operation; and energy export from a solar array.
- Charge and discharge a lithium-ion battery bank concurrent with simultaneous operation of the solar array, while synchronized to the electric grid.
- Volt / VAR control, manually controlled via a web interface, showing remote operation capabilities.
- Interpret and respond to the “7 communication and control functions” from 61850 / DNP3.
- Manually disconnect grid power and transition to backup power support of a dedicated load for a reasonable amount of time.
- While in off-grid mode, manually reduce solar power and show steady power and voltage (battery output automatically increases to compensate).
- While in off-grid mode, shut-down a small load using a “smart relay” to show technical intelligence based on reaching a battery State of Charge (SOC) set point.

9. IMPACTS FOR THE UTILITY, CUSTOMER AND PV APPLICATIONS FUTURE

9.1. Pricing Versus Value

9.1.1. Pricing

Pricing for the commercial DRI is set at $0.75 per watt, or $75,000 for a 100kW DRI, for the first beta units. These will be used in demonstration projects with utilities and technical customers, primarily as a way to vet the product and technology commercially and to prove commercial benefits prior to potential mass deployment.

PPS projects early pricing for the commercial DRI in larger runs at $0.65 per watt. While this is higher than a commercially-available two-port solar inverter (typically $0.30 – $0.50 per watt), the benefits of the DRI are two-fold—ease of integration with energy storage sources and microgrid systems, and advanced grid-support functions such as VAR control, demand response, and frequency regulation. Each of these advanced functions provides additional value and revenue streams to an installation, essentially paying for the advanced functions.

At these prices, PPS anticipates gross margins over average selling price to be 30-40%, which is standard for the industry and reasonable for a new high-tech product with an anticipated high market growth rate.

9.1.2. System Benefits

In the pricing discussion it is also important to put the DRI component into the context of the full system. A commercial solar system today can be installed for $4 – 5 per watt once everything is taken into account. Of this, the inverter itself accounts for $0.30-0.50 per watt, amounting to less than 10% of the total. Adding a storage component to the system varies in cost, but will typically be between $1 – 4 per watt. The engineering and programming required to design and install a system, including energy storage (in order to take advantage of the additional revenue streams available with storage) can range anywhere from another $0.50 – $2.00 per watt or more.

Thus, the premium cost of the DRI ($0.65 versus $0.30 per Watt, or $35,000 for a 100kW installation) is far less than the cost of designing and installing an equivalent “advanced” system using today’s technologies and best practices.

From a marketing perspective, these “advanced” systems represent a small percentage of the PV systems that are installed annually in the U.S. and worldwide, but it is a growing segment and PPS believes it is the key to achieving high penetration and integration rates for solar electricity on a large scale. Systems including storage and grid-support functionality allow higher PV penetration rates, improve grid efficiency and reliability, reduce the cost of transmission and distribution upgrades, allow greater facility or host site efficiency and reliability, and ultimately lower the cost of integrating PV generation.

9.1.3. Achieving $1/Watt

The DRI was designed as a modular, configurable technology and product platform. While we consider the “Cadillac” DRI to be the four-port machine that allows easy integration of energy storage, solar, microgrid control, and a utility grid, the DRI platform can also be configured as a simpler two-port machine directly connecting PV to the grid. The advancements made in the nanocrystalline core inductor design, high-frequency isolation, and packaging, discussed in sections 5.5 and 7.3.7 all apply to the two-port platform, and in this configuration and in the future will be capable of meeting the targets for the $1/Watt commercial-scale PV installations.

This system will have some limitations in its ability to provide all Demand Response functionalities, peak shaving, frequency regulation, and other grid-support features, but will provide high-efficiency, cost-effective interconnection of commercial-scale PV with the grid.

Further testing is required to commercialize this different configuration, but the basic technology has been tested and proven as part of this program.

9.1.4. Single-phase DRI (10kW)

Separate from the current SEGIS project, PPS is investing in the development of a single-phase smaller-scale DRI product. The product will share interface features and basic functionality with the larger-scale DRI, but will be geared toward residential and small commercial applications. The electric vehicle charging and military operating base markets have been particularly enthused about the 10kW product.

The following is a recommended pricing list for the single-phase DRI. The pricing list below is for a 10kW model, and this pricing on a per-kilowatt basis would apply for all DRIs in the range of approximately 3,000 – 20,000 Watts:

- $9,999.00 USD for Qty. 1-9
- $7,999.00 USD for Qty. 10-24
- $6,999.00 USD for Qty. 25-99
- $5,999.00 USD for Qty. 100+;

9.2. U.S. Jobs Discussion

When the SEGIS Stage 1 project was first initiated at PPS, the company employed 15 people in a 6,000 square foot facility. Today as we near the end of Stage 3, PPS employs roughly 50 people, operates four facilities at a total of approximately 33,000 square feet, and has become one of the largest manufacturers of clean energy products in the State of New Jersey.

This company growth and the jobs that have been created by PPS are directly attributable to the support of the SEGIS program. While our team sells various products and is developing various technologies, both under the SEGIS project and outside of it, the SEGIS program has provided a multi-year vehicle for hiring high-level engineering and technical talent to advance the PPS platform technologies and prepare them for commercialization.

In 2009, PPS embarked on a multi-year program to invest over $6M in an advanced manufacturing facility and solar/battery demonstration facility in New Jersey, which are now nearing completion. The DRI is one of the primary products we plan to manufacture in the new facility. This program has led to the creation of more than 10 manufacturing and production jobs, and PPS expects it to lead to the creation of many more jobs in the near future. We currently project ramping employment up from the current 50 people to more than 90 people within the next two years.

In addition to the many new jobs at PPS, our growth has had a direct effect on our suppliers, creating even more jobs throughout the supply chain. For example, over the past several months we have purchased more than $200,000 in metalwork and cabling from local suppliers, directly leading to the creation or retention of several employees at several companies.

PPS believes that PPS, and the clean energy industry as a whole, are in the first stages of a long growth curve. This industry in particular lends itself to job creation for not only manufacturing, but also for on-site installation and support of energy systems. The products PPS manufactures tend to be large and expensive to ship, making it less attractive to outsource manufacturing and more attractive to manufacture close to the point of use. Installations in North America lend themselves to having teams of local people to design, install, and service the system, which can lead to hundreds of jobs for the number of systems that PPS believes will be installed over the next few years.

9.3. Long-term Standardizations

9.3.1. Time-of-Use Pricing

Time-of-use pricing is key to the deployment of many grid modernization technologies, and the DRI and related systems benefit from these pricing scenarios. While they are common in some utility service areas, they are not nearly as prevalent as PPS would expect them to be. In almost all cases, it is proven that costs of generating and delivering electricity vary with time of use, so it makes sense to vary pricing with time of use. PPS believes time-of-use pricing will become more and more prevalent in the coming years.

9.3.2. Utility Service Automation

Distributed resources can provide significant benefits to utilities when operating either in an automated or controllable manner. While the “holy grail” of distributed resources is to have each resource available and controllable by the utility operator, the security and operational challenges this presents make it difficult at the moment. Many of the benefits an inverter can provide, however, such as VAR control, can be programmed to happen automatically. In this way, the advanced features can benefit the utility directly, without requiring immediate integration into the utility control system.

The challenge is to monetize these benefits in a way that works for the utility and is economic, but also provides certainty to the asset owner and investors.

9.3.3. PJM / FERC Regulations

Distributed generation revenue sources for many markets in the Northeast are controlled by PJM. We see a trend toward distributed assets participating in markets that have traditionally been dominated by central generation and utility plants. For example, battery storage systems as small as 500kW can provide area frequency regulation services to PJM. PPS sees the trend continuing toward smaller resources (e.g., 10kW) participating in these markets, and ease of interconnection for these systems. This will lead to faster deployment of these assets, and a need for communications to tie them together.

PPS also believes there is an opportunity to modify the way that Capacity Factor is valued for intermittent renewable resources, especially with the addition of energy storage to these systems. A solar array or wind farm operating together with an appropriately-sized energy storage bank can provide capacity upon demand, and therefore should command a near 100% capacity factor disbursement.

10. SUMMARY AND CONCLUSIONS

Princeton Power Systems, Inc. (PPS) has progressed from the conceptual design and market analysis, through prototype development and characterization, to now producing pre-commercialized 100kW Demand Response Inverter (DRI) Systems during the three-stage Solar Energy Grid Integration Systems (SEGIS) program. The work was completed on time under contract from Sandia National Laboratories. The SEGIS program is a part of the broader DOE Solar Energies Technologies Program, which has the objective of bringing the levelized cost of energy (LCOE) of grid-interactive PV systems to parity with the electric grid by 2015 by developing advanced technologies that are lower cost, higher efficiency, modular, and synergistic with other energy conversion and producing systems. The early goals included technologies that result in a system LCOE of $.05-$.10/kWh as a high priority. The recent DOE Sunshot program aims for $1/W for large systems and also benefits from SEGIS developments.

The DRI product design contributes to the desired goal of $1/watt PV system cost and LCOE cost target of $0.10/kWh through its innovative four-port topology that is flexible for use with or without energy storage and has the capability to communicate with interconnected power and flexible loads. The DRI enables two-way commanded power flow to optimize the value of its renewable energy source and to provide stabilizing features including VAr support, low-voltage ride-through on stressed grids, and power curtailment that will allow for higher penetration of PV systems into the nations electrical power grid.

PPS is confident that the DRI controller is a promising technology that can provide a commercially viable interface for more PV system integration into the utility grid. The controls and communication features allow the units to actively communicate with other units and with the energy management system to work in a distributed-generation grid. The DRI will increase market acceptance of PV by further incentivizing end users to consider PV installations. It will provide an improved economic payback based on lowered LCOE, and will also provide additional economic incentives that a traditional PV system does not. For some customers, the critical functionality of energy management and load control are the primary reasons the DRI is attractive. Furthermore, the DRI technology will assist utilities and grid operators with solving the issues of high-penetration PV integration and their own peak-power requirements. PPS believes that the DRI functions will become a required technology for new PV installations based on its ability to communicate and interact with grid operators.

The SEGIS DRI project has opened many new opportunities for PPS to develop systems similar to the DRI for other renewable energy applications, thereby helping the growth of PPS and green energy, which will reduce dependency on oil and natural gas and create jobs in the United States. The PPS production facility is now expanded and preparing for initial production quantities of 60-70 units per year.

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