# Final Project Report

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ALENCON

# 1. Executive Summary

The objective of this project was to fully develop, demonstrate, and commercialize a new type of utility scale PV system. Based on patented technology, this includes the development of a truly centralized inverter system with capacities up to 100MW, and a high voltage, distributed harvesting approach. This system promises to greatly impact both the energy yield from large scale PV systems by reducing losses and increasing yield from mismatched arrays, as well as reduce overall system costs through very cost effective conversion and BOS cost reductions enabled by higher voltage operation.

Over the course of the project, Alencon built an excellent team of engineers from scratch, modeled, designed, simulated, prototyped, and finally completed multiple iterations of the power electronics in the system. This culminated in the achievement of just about every highly aggressive goal defined at the beginning of the project. While the overall goal of the project was to create and commercialize both a 10MW inverter system and 25kW DC/DC converters operating at 2,500V, technical metrics included conversion efficiencies of 99% for both sub-systems, cost targets for the power electronics of 10¢/W, 25 year reliability, and more. The vast majority of the targets were reached, culminating in LCOE cost reductions, and power electronics costs pushed to well below the original goal. The final design of the inverter and DC/DC converters stretched into the year after the completion of the DOE project, with the first commercial DC/DCs scheduled for release from a contract manufacturer. The certification process was under way on the inverter by the end of the project, and was expected to begin for the DC/DC once they were received from manufacturing. Alongside DOE funding a private investment commitment of $6M was made, with funds allocated for release along the milestones outlined in the SOPO of this project.

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## 3. Background

At the time of the award announcement, the SunShot initiative had set out to "achieve a total installed cost for utility-scale PV systems of $1 per watt." This goal was "further broken down into three components: $0.50 per watt for modules, $0.10 per watt for power electronics, and $0.40 per watt for installation and remaining balance of system (BOS) costs" (DE-FOA-0000479). Alencon was convinced it would be able to achieve the power electronics aspect of the goal, while at the same time reducing overall costs of the system through a better topology and increase system yield.

While the cost of PV modules and equipment has dropped over the years, the BOS costs (including cables, materials, switchgear, and labor) had not followed suit. Designers and installers made the best of available technology, but this with limited effect on BOS costs.

Conversion efficiencies increased on a unit level, yet overall yield has taken a hit in many of today's utility-scale systems that use larger capacity inverters. The drop off in yield has occurred for a variety of reasons, including ever greater numbers of strings placed in parallel with mismatched operational parameters (coarser MPP control). Maintenance of equipment is a necessary cost for any PV system and is a big part of the financial analysis made by the developer or EPC during the early stages of a project. The tradeoff lies between more expensive but more reliable equipment, versus lower upfront cost with greater maintenance costs down the road.

As systems have grown and the industry landscape has changed, designers have found that there are many drawbacks to pushing the traditional approach of using multiple "central" inverters in larger and larger systems. Seemingly more and more engineers are looking to overcome one or more of these problems in creative ways, even going so far as to using hundreds or thousands of smaller string inverters rather than multiple larger inverters. This has the advantage of making the design and installation easier and faster, while allowing for MPP tracking with significant granularity, increasing yield. However, BOS and equipment costs are higher with such an approach, and communicating, controlling, and ensuring grid stability with such systems becomes a nightmare. Even though string inverters address certain issues, they come with their own set of challenges and drawbacks.

This leads to the conclusion that neither centralized nor string inverters provide a great solution when creating utility-scale solar fields. The ideal solution would combine the best of both of these types of systems to achieve a utility-scale solar installation with:

- Reduced BOS costs
- Quick and easy installations
- Greater yield and granularity
- Central interconnections
- Single point of communication and control
- Great reliability
- Low impact of equipment failures

This is precisely what Alencon set out to provide.

# 4. Introduction

The Alencon topology is the only utility scale PV architecture that uses a single, central inverter system, with up to 100 MW in capacity, and a string-power-optimizer-based distributed DC harvesting network. The Alencon central inverter is not another PWM product, but is based on current-fed Harmonic Neutralization technology patented by Alencon, and does not suffer the same drawbacks that normal central inverters do.

The Alencon system includes:

1. String-wise power optimizers
2. A high voltage DC bus
3. A single modular central inverter
4. Control Monitor System
5. SCADA system
6. Graphic visualization of the PV plant

Strings of PV panels are connected to String Power Optimizers and Transmitters (SPOTs) that harvest the maximum amount of energy from each PV String. Additionally, Alencon SPOTs convert the strings' low voltage/high current into high voltage/low current for DC transmission to minimize losses and reduce cables costs.

All the optimizers' outputs in a utility-scale solar power plant are connected to a common DC bus of a single inverter. The inverter is modular, so capacity can be scaled in discrete units. This also allows for redundancy to mitigate the effect of equipment failure. AC outputs of each module are combined on one or multiple output transformers to raise the AC voltage to the electrical grid level. The System Master Controller (SMC) manages the operation of the system, and provides a single interface the Alencon system, regardless of size. A local monitor collects performance data of every string, SPOT, and GrIP in the system, which can be viewed by customers, engineers, and operators through a proprietary graphic display system (VIEWS) in real time from any location in the world.

The project was broken down into several tasks to guide development. Each task describes the milestones and subtasks to be completed to achieve each of these goals.

High level tasks included:

- Creating the Proof of Concept (PCP) Prototype GrIP
- Designing and building a power lab for GrIP testing
- Creating the PCP SPOT
- Updating the PCP GrIP to a Pre-Production Prototype (PPP)
- Updating the PCP SPOT to a PPP
- Determining system benefits, modeling controls, and communications
- Inverter system testing and certification
- SPOT testing and certification
- System integration

- Beta PV system engineering, certification, and field validation testing
- Prepare GrIP and SPOT designs for production

These topics will be discussed in the following section.

# 5. Project Results and Discussion

## 5.1. Phase 1: Initial Designs, Modeling, and Preparations

### 5.1.1. Task 1.0: GrIP PCP

**Description:**

Work completed prior to DOE award mostly consisted of prototyping the GrIP design, software, communications, controls, etc., for purpose of initial testing and verification of operation principles. However, in order to enable the highest level of capability, all levels of design had to be overhauled. Therefore the completion of the research and development as well as testing of the lab-grade prototypes was the starting point of the proof-of-concept phase. The results of this continued testing would be used to finalize the design of the inverter system, and create and verify operational models for in-depth simulation.

The Alencon inverter system operates with what has been termed Harmonic Neutralization (HN) technology, and consists of a number of high power current source inverter modules (GrIPs), each operating at line frequency (50 or 60Hz). The current waveform, including harmonics, generated by each module are staggered with respect to one another with an optimal shift in phase. The output currents from all modules are summed in a step-up transformer and fed into the electrical grid, with near perfect sinusoidal waveform, see Figures 9, 17 & 18.

HN technology scales up to tens of megawatt, with Alencon inverters being the only ones in the industry that do not use the PWM technique.

#### *5.1.1.1.SubTask 1.1: Complete PCP Units*

The project started with a single operational PCP GrIP and three partially assembled enclosures. Some updates needed to be made to the operational unit, and the remaining three needed to be completely assembled, wired, and subjected to basic testing. In addition to the hardware work, the control board design needed to be updated, and the software framework reworked.

In the second and third quarters of the year, additional communication and sensor capabilities were added to the GrIP Control Boards (GCBs), and a software framework emphasizing modularity and well-defined state machines was developed for use during the remainder of the PCP phase. Documentation, design processes, and software requirements specification procedures were evaluated and implemented. One of the few remaining single points of failure in the design of the inverter system was the communications link to the GrIPs. This had to be updated to allow for redundancy, which was added in the newer GCB design.

In parallel with the completion of the four PCP GrIPs and the new PCB design with redundant communication capabilities, work also continued on the control software and system simulations. Updating and restructuring the software allowed for faster turnarounds on development, allowing engineers to more rapidly prototype, modify, and test software. It also provided greater quality control for existing source code and enabled smoother transitions from the prototyping phases into production and support.

By the end of the third quarter eight new GCBs were in production, which would give advanced communication capabilities and more processing power to the inverter modules. At the same time, the GrIP hardware was updated to allow for full-current capacity (1,000A) at medium voltage (750V).

By the end of the fourth quarter 2012, all four units were completed and fully-functional. Additionally eight second-revision GCBs were received and the layout and component placements were verified.

#### *5.1.1.2. SubTask 1.2: GrIP and Inverter System Testing*

Initial testing of prototypes all occurred in borrowed space owned by what was previously Alencon's parent company. Limitations at this location included a maximum available power of ca. 400kW and voltages around 700V. Testing of PCP GrIP 1 at this location was to be completed up to the maximum capacity of the lab, after which continued testing needed to be placed on hold until Alencon had outfitted a lab with sufficient capabilities. In terms of operational current, which for the current-fed design is the most important, this unit was successfully tested to over 50% of its capacity. The completion of testing of the safety measures and basic controls on this unit would also help ensure a swift and smooth progression of testing for the other three PCP GrIPs.

In Q2, with the goal of certifying the equipment already in mind, an initial certification plan for the Alencon inverter system was created to summarize the approach in certifying the utility-scale inverters. Discussions also began with potential customers, giving insight to the certification plan and their perceived requirements. The Construction Guidelines document was initiated to guide design and meet the functional and regulatory product market requirements for the GrIP and SPOT products in North America.

By the end of Q3 2012, GrIP controls were tested on all units, with all four GrIPs being ready for full power testing and interleaved/parallel power testing. All GrIP units passed the initial test phase, and Unit 1 was subjected to higher current testing.

Finally, in the fourth quarter of2012 the first GrIP unit was tested to full capacity (1,000A), and all operation of all protection schemes, controls, and communications were verified up to this level of current. Additionally, the operation and topology was proven when testing commenced with multiple units under manual control, which verified that a combination of four GrIPs switching at 60Hz would create a clean sine wave output (see SubTask 2.3).

#### *5.1.1.3. SubTask 1.3: GrIP Modeling and Analysis*

A MATLAB/SIMULINK model of the GrIP device was produced and compared to actual measurements for model verification, see Figure 1. One of these models consisted of four GrIPs to analyze their capability

for high power testing with power recirculation. This also established the GrIPs capability of operating as Dynamic Reactive Power Generators, see Figure 2.

The performance of the model was evaluated and compared to one of the PCP units. Once the aforementioned model was verified, a set of four GrIPs were modeled to work together connected in parallel using a common DC source and a passive load. This allowed for the analysis of the system under various conditions, for example showing perfect output waveforms, great voltage regulation capability, and excellent power factor controllability through timing control variables. In Q3 a full-time engineer and part-time control expert were hired to complete development on the active control schemes. The Simulink model was then outfitted with PID current controls for active grid simulations.

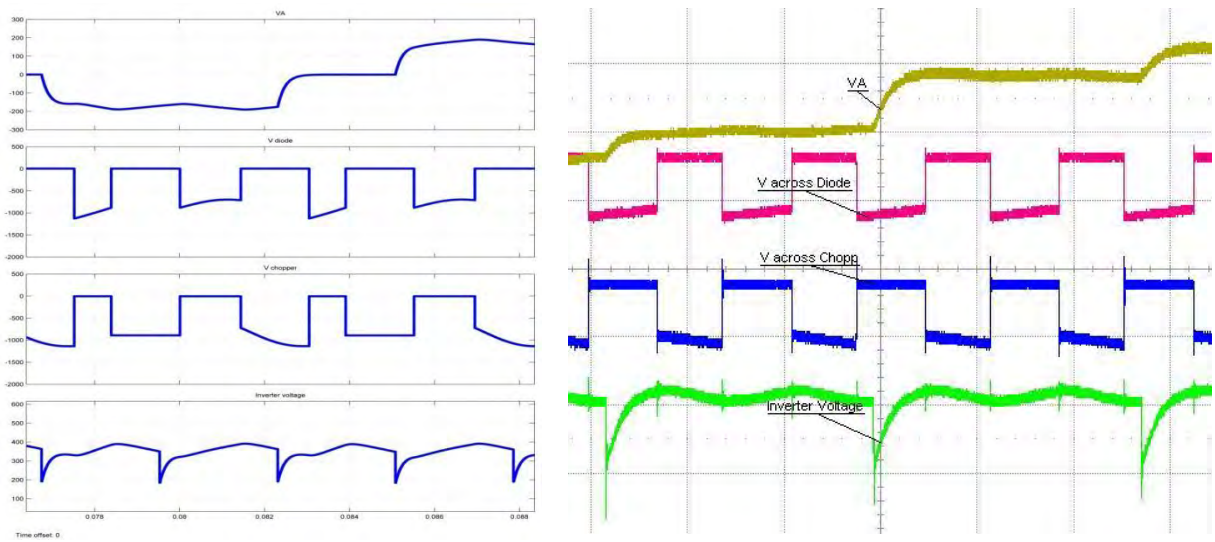



**Figure 1. Modeled vs. Actual Waveforms**

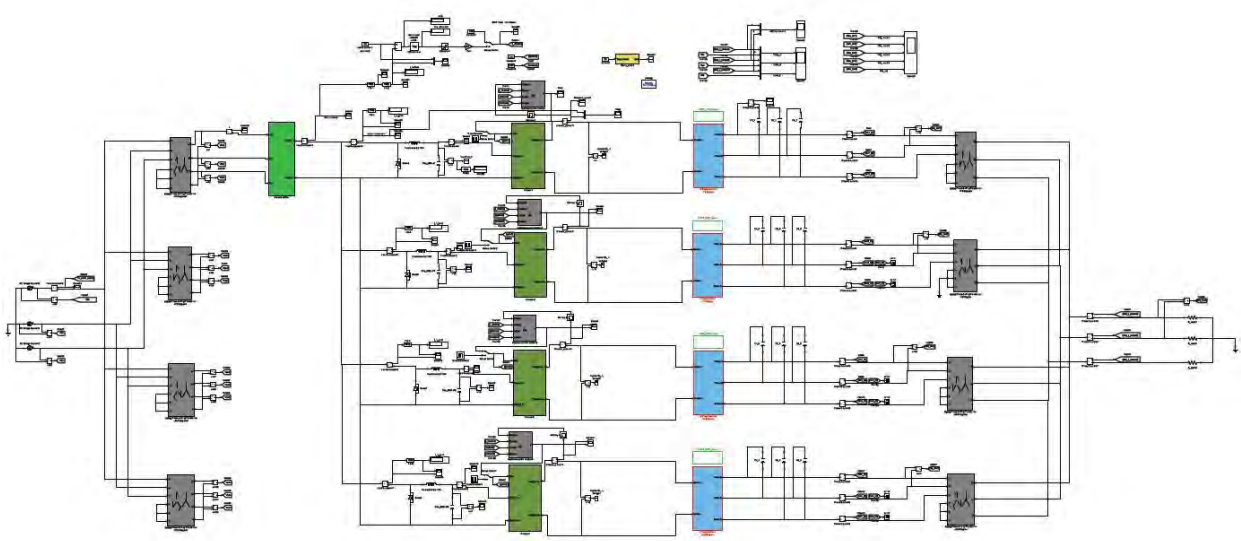


**Figure 2. Full Scale Inverter Model in Simulink**

#### *5.1.1.4. SubTask 1.4: Test Software Environment for Multiple GrIPs*

The software for multiple GrIPs had to be designed and created in order to enable proper control of the inverter system during testing. Development of a console application establishing network communications between a Windows PC and the GrIP control boards was completed, as well as an initial draft of the GrIP Monitor Graphical User Interface. The pre-alpha phase of development of this GrIP Monitor, a Microsoft Windows based application for controlling and logging data from multiple PCP GrIP units, began in Q4. Part of the work completed included the specifications for the interoperability of four GrIPs and a master controller. The user interface for control, diagnostics, and troubleshooting purposes was specified, and basic ethernet communication for PC control of unit operation was implemented.

By the end of Q4 2012, the first iteration of test environment was complete and tested. User control capabilities for multiple units were also completed and tested.

### 5.1.2. Task 2.0: HV Lab & Grid Testing

One of the major tasks under this project was the design and construction of a power test lab for subsequent testing of GrIPs at the full operational voltage (2,500V). This test lab would be utilized not only for the initial verification & certification of the equipment, but also for internal testing before shipment. Along with the design of the necessary equipment such as the centralized bus housed in a "dock", testing of equipment within the lab had to be completed. Three subtasks were created to effect these developments: one to build the lab, one to create the dock, and a final one to test all four units with this equipment.

#### *5.1.2.1. SubTask 2.1: Build HV LAB*

The necessary components for the HV lab, such as load banks, transformers, and test peripherals required to run the equipment would need to be procured, and the lab would need to be outfitted to ensure safe and proper handling of high power equipment.

In Q1 and Q2 of 2012, most of the equipment necessary to build the test lab was specified and placed on order. With long lead times on most of these items, ordering the equipment in the first few months was imperative to receiving it all when the HV lab would need to be outfitted. Since all of the items were necessary for the testing of the GrIPs, delays in the receipt of any of them would have impacted the schedule.

In Q2 2012, Alencon found a suitable location for their offices, and negotiated and signed a 3 year lease (with the option of extending by 3 years) for the new location, which included a dedicated 1,000kW electric power feed for inverter testing. Renovations on the space began by Q3, and contractors were selected for electrical, water, etc. installations.

HV lab build-out was in progress by Q3 and lab equipment was ordered with a majority of items being delivered for a tentative equipment move-in date of August 1 2012.

The first stage of outfitting the lab included the installation of:

1. 1,000kVA Utility Feed
2. 4,160V disconnect
3. 1000kVA HV transformer
4. 480V disconnect
5. 1,000kVA variable voltage transformer
6. 7,000kW rectifier
7. Four GrIP prototypes
8. Four Docking Stations
9. 24 Pulse 1,000kVA Zig-Zag output transformer
10. Internal closed loop de-ionized water cooling system
11. External open loop raw water cooling system with Delta evaporating tower
12. 1,000kW forced air cooled resistive loads
13. Four 125kW convection cooled resistive loads

**Figure 3. GrIP Units**

Figure 4. Internal Water Cooling System

Figure 5. HV Switchgear and Transformers

By Q4 2012, HV lab build-out was completed with all equipment installed and tested.

### *5.1.2.2. SubTask 2.2: Design and Build GrIP Docking Stations*

In order to test the GrIPs, a point of connection had to be created and installed in the lab. The basic design of the GrIP docking stations was completed to ensure that testing could commence in an environment closely matched to the final commercial system.

Figure 6 shows the docking station design, including contactors and low voltage AC disconnects. Figure 7 gives the final design and actual installation of the dock with the four PCP GrIPs. Initially, the dock was wired to a single unit for full-current capacity testing.

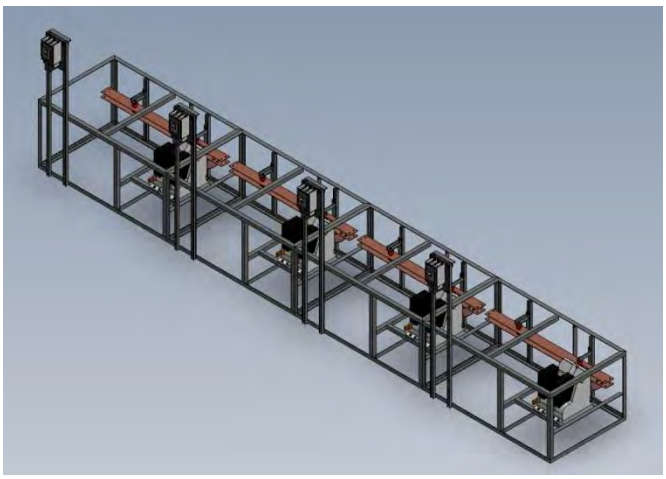


**Figure 6. Docking Station Design**

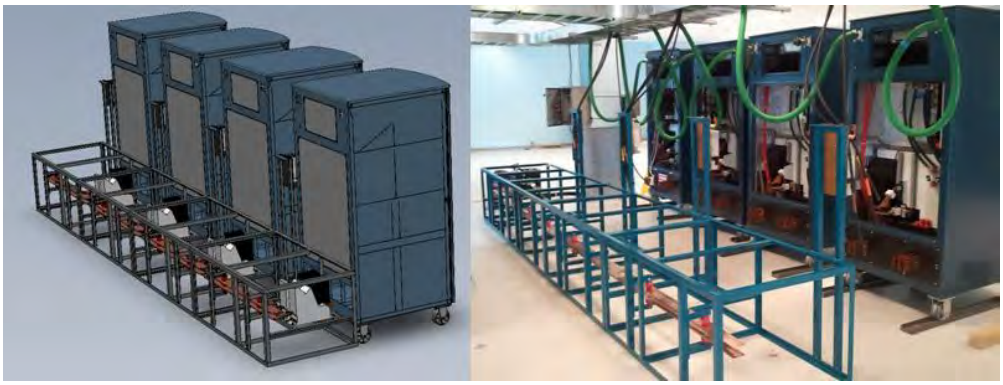


**Figure 7. Docking station design & implementation**

By Q3 2012, the prototype docking stations were complete, with one set of 1,000A 2,500V contactors in place for testing. It included the single copper bus that would supply the inputs of all four units. In early Q4 they were completely wired (see Figure 8) and operation was verified during testing.

Figure 8. Completed Docking Station

### *5.1.2.3. SubTask 2.3: Test Four PCP Units at MV*

This subtask included the complete testing of the four MV PCP GrIP units working as one inverter system to verify the phase-shifting concept. Initial testing of multiple units showed a perfectly sinusoidal output waveform with virtually no harmonic distortion.

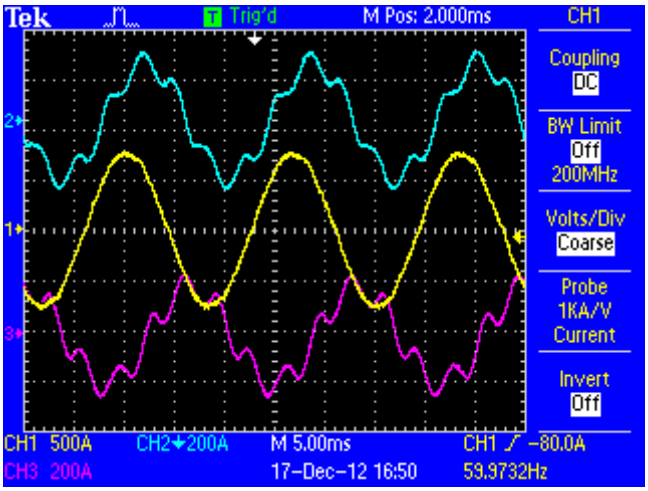



Figure 9. Phase shifting transformer input (two units - blue and red) and output (yellow)

The individual GrIP outputs matched precisely those that were modeled earlier, as did the output waveform. Figure 9 shows two GrIP outputs (one in blue, the other in magenta) and the final output waveform after the phase shifting transformer.

### 5.1.3. Task 3.0: SPOT PCP Hardware

#### Overview

This task focuses on the modeling, design, and creation of the SPOT PCP Hardware and Software for initial testing of the DC voltage boosting device. The task was split into three subtasks: Modeling and Simulations, Creation of the Prototypes, and Testing.

The SPOT is an isolated DCDC power converter, which utilizes a full bridge inverter and rectifiers to convert the DC signal to AC, step it up and convert it back to DC. The DC input signal (up to 1000V) comes from the PV modules it is connected to. The SPOT converts the DC signals using a full bridge inverter into rectangular shaped AC signal. The output of the bridge is connected to the LLC circuit, which consists of an inductor, capacitor, and transformer.

The resonant circuit provides great functionality which helps to achieve high conversion efficiencies. The losses are the smallest at the resonant frequency due to a soft switching technique (zero voltage and zero current switching). The voltage (and transformation ratio) is controlled by the frequency. Operation below resonance boosts the voltage, while operation above resonance reduces the ratio. The PV MPPT point is maintained by adjusting the frequency of the bridge.

The transformer in the circuit is used to isolate the output from the input and to provide a nominal ratio between the secondary and primary voltage levels.

The rectifiers on the output are used to convert AC back to the DC to feed into common high voltage bus for the GrIP inverter.

The table below shows the comparison between PCP unit (Boost + DCDC converter) and the PPP Spot versions.

| Parameter | PCP Unit | PPP Unit | Description |
|---|---|---|---|
| Input Voltage | 200V – 750V | 200V – 1000V | Input voltage range while SPOT circuits operate, but not convert power |
| Input Operating Voltage | 300V – 750V | 300V – 1000V | Operating voltage range with the DCDC converter operating |
| MPPT Range | 400V- 750V | 500V – 800V | MPPT regulation range |
| Output Voltage | 2000V | +/- 1250V (2500V) | Output bus voltage |
| Rated Power | 20 KW | 25 KW | Rated power |
| Peak Efficiency | 97.3% | 98.6% | At 3kW output power |
| Communication interface | Wired only, (Rs232), MIWI only evaluated | Wireless MIWI PRO | Communication with the SPOT unit |
| Housing /Environment | Indoor only | IP67 | First PCP did not pass the environmental test |
| Size / weight | 21”x 12”x 12” 120lbs | 23”x11”x 15” / 85lbs | The PCP housing consist from single off the shelf profile and custom cover. The PPP housing is custom designed and consists from two heat sinks with optimized cooling optimization |

| | | | |
|---|---|---|---|
| Number of PCB boards / assembly | 4x Power Board<br>4x Control Board<br>1x Communication Board | 4x DCDC Converter Board<br>4x Magnetic Interconnect<br>1x Communication / Combiner Board | The PCP unit was not production friendly. The transistors were attached to the heat sink extension bars with long screws. The magnetics cables were soldered to the PCB after they were mounted to the heat sink. The PPP unit fits the DCDC board directly and is attached by the clips. The magnetics is assembled separately and the harness is attached to interconnect and combiner boards using spring clips. The control and power boards were combined into the DCDC board to reduce the cost and reliability (PCB sizes / connectors). |
| Key components | 5x SiC Transistor<br>8x SiC 10A Diode<br>5x Discrete Drivers | 4x SiC Transistor<br>16x SiC 5A Diode<br>2x Optimized Drivers | The PPP unit was besides a performance boost also optimized to be more cost effective. The transistor drivers were optimized and less expensive diodes were used. |

#### *5.1.3.1. SubTask 3.1: Device Modeling and Simulation*

Starting in Q1 2012, the first model for SPOT simulations was implemented and evaluated using PSpice. This model was eventually reworked with the help of Matlab's Simulink toolbox, which provided a more powerful environment for simulations and modeling.

Various DC/DC converters were analyzed, with a resonant topology looking the most promising for the power levels and voltages that the device would be subjected to. Concerns about the controllability of the resonant topology for MPPT purposes brought about simulations that would test the ability for the topology to control input load with operating frequency. Additional simulations included advanced circuit controls for power circulation through the SPOT, which would prove to be useful for testing the hardware.

By Q4 2012, simulation models of the following were completed:

- full bridge resonance DC/DC converters
- half bridge resonance DC/DC converters
- strings of photovoltaic modules
- a "smart load" utilizing a buck converter to vary a load to maintain a constant voltage on the output of the DC/DC converter
- an entire assembly containing four strings of modules, four full bridge DC/DC converters all operating with a "smart load"
- a basic MPPT algorithm to control the converter

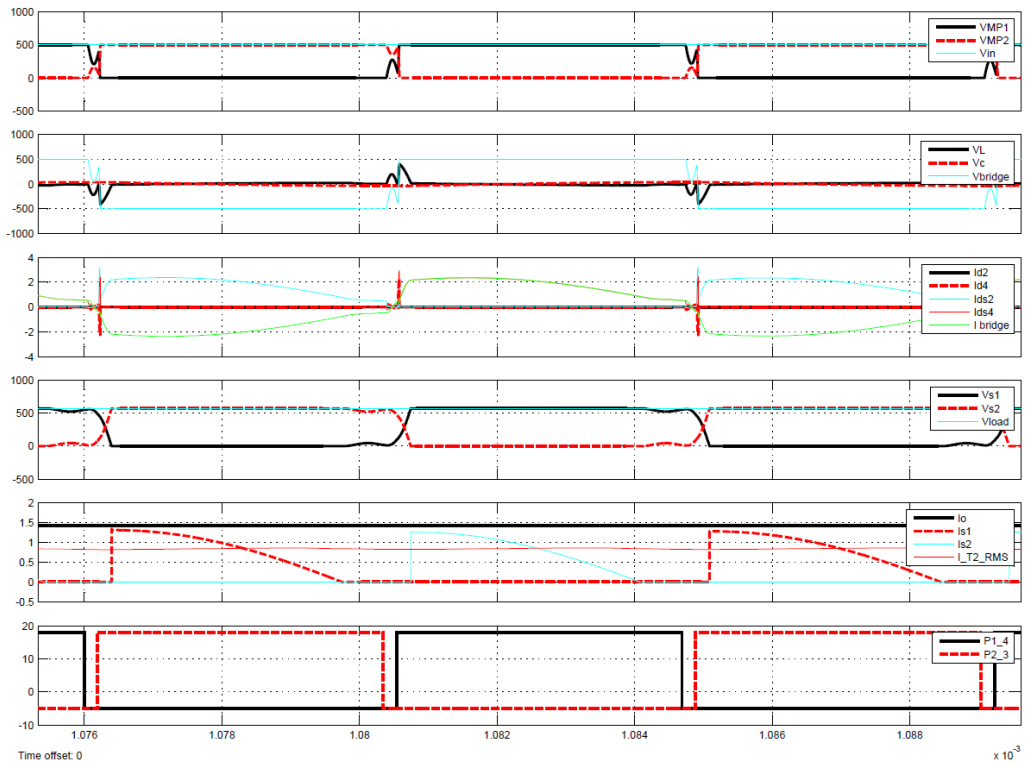



Figure 8. Simulated SPOT waveforms

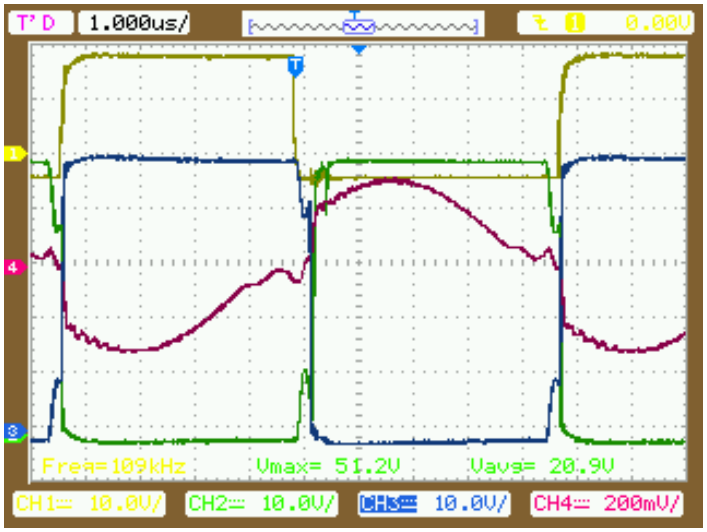



Figure 9. Bridge current, voltages and gate command of the experimental results

As can be seen in Figures 8 and 9, final SPOT models and simulations almost perfectly matched the waveforms generated in physical testing. Shown here are bridge currents (sim: Ibridge, real:magenta), switch voltages (sim: VMP1, VMP2, real: blue, green).

### *5.1.3.2. SubTask 3.2: Build PCP SPOTs*

The first potential prototype designs were completed after analyzing various topologies with the help of the modeling and simulations completed earlier. Alencon worked with outside hardware and software contractors on the construction of the first bench-top prototype. This verified switching and circuit operation with a breadboard electrical and basic mechanical prototype, with the first design ready for PCB implementation.

By the end of Q2 the bench-top prototype of the first SPOT design was completed and basic controls implemented for testing. The first PCB boards had also been designed and manufactured, and were ready for implementation. Research on the wireless hardware and communication network design began, with the selection of the transceivers boards following soon thereafter. Preliminary controls were implemented on a micro controller, with the user interacting via a display and button controls that allowed for a limited range of input frequency variations and for the measurement of input current and voltage. Q4 began with the design and construction of several versions of both the full bridge and half bridge topology, see Figure 10 and Figure 11. The second revision of the full-bridge DC/DC converter was completed as well and testing of it began (Figure 11).

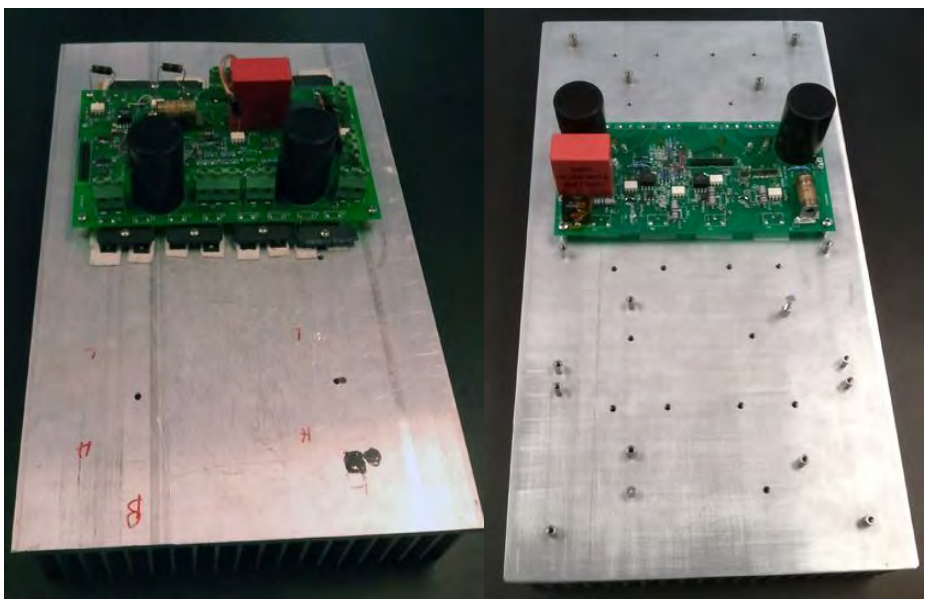


**Figure 10. First and second iteration of full-bridge DC/DC**

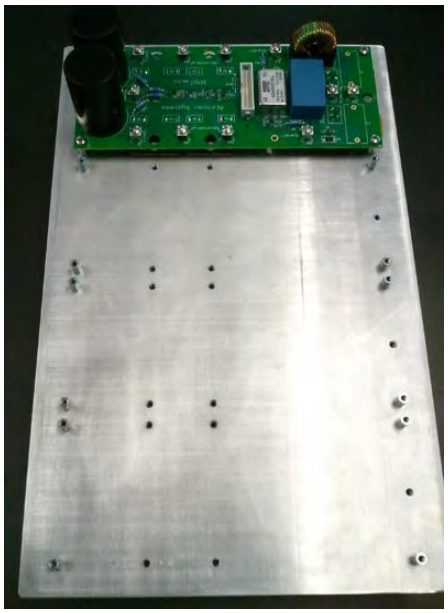


**Figure 11. Half-bridge DC/DC Converter**

Testing of the full bridge DC/DC converter began in the range of 15 to 30 kHz, and control of the resonance topology with variations in frequency to support MPPT was verified. However, the size and cost of the associated magnetic components (inductor and transformer) were found to be too large and did not meet the requirements of the project. The decision was made to design another board operating in the range of 80 to 120kHz with significantly smaller magnetic components.

#### *5.1.3.3. SubTask 3.3: Build Test Station and Commence SPOT Operational Testing*

A programmable power supply was selected to act as the string simulator for the input of the prototypes. This allowed for MPPT testing at full DC/DC converter power levels as specified by the design. A small smart load and control circuits were installed for SPOT testing, completing the first basic test station.

In Q4 2012, the SPOT test station was completed, including the use of an 8kW string simulator, a variable 300 ohm 7.2kW resistive load, and a smart load controller. The full bridge DC/DC converter was tested in the range of 15 to 30 KHz, utilizing the 8kW PV string simulator as a power source and the resistive load as the sink.

The completed 8kW SPOT test station included:

- 8KW PV string simulator
- 300 Ohm, 7.2kW resistive load
- "Smart load" controller
- Four full bridge DC/DC converters
- Four rev 2 full bridge DC/DC converters
- Four half bridge DC/DC converters

### 5.1.4. Task 4.0: Project Management and Reporting

The team grew to six full time employees by Q2 2012, starting with the addition of a new CEO, an administrative manager, a director of marketing and compliance, as well as an additional electrical engineer. By Q3 the addition of an embedded software engineer, a simulations and controls engineer and a test engineer brought the group size to nine. In this quarter, Alencon participated in the SunShot Grand Challenge Summit and Technology Forum in Denver Colorado.

#### *5.1.4.1. SubTask 4.1 Qualification and Selection of Beta Site*

Discussions with potential beta test partners for first GrIP and SPOT systems continued. The prevailing plan at the time was to identify a site requiring inverter replacements and retrofit existing inverters with Alencon's, possibly to achieve a side-by-side comparison against a traditional central inverter topology. The company also attended Solar Power International Show in Orlando, Florida, where great turnout for our booth and a wide customer base that seemed interested in finding new solutions to allow them to continue to supply PV systems in the coming years. 2012 through 2014 were anticipated to be tough consolidation years where having an edge over the competition in terms of system yield and costs, would potentially be become even more important.

## 5.2. Phase 2: Pre-production prototype and design

### 5.2.1. Task 5.0: GrIP PPP to Certification

With the data from GrIP PCP testing and reviews of the design, the next iteration of the GrIP was to be created. This pre-production prototype would include most of what would be necessary to achieve UL 1741 certification.

This task was broken down into four sub-tasks: The design, simulations and modeling, manufacture and testing, as well as planning the path to certification.

#### *5.2.1.1. SubTask 5.1: Complete PPP GrIP design*

By Q1 2013 the first iteration of the PPP GrIP implemented items improved upon from PCP design. The GrIP software was successfully ported to the second revision of the control board during this quarter as well.

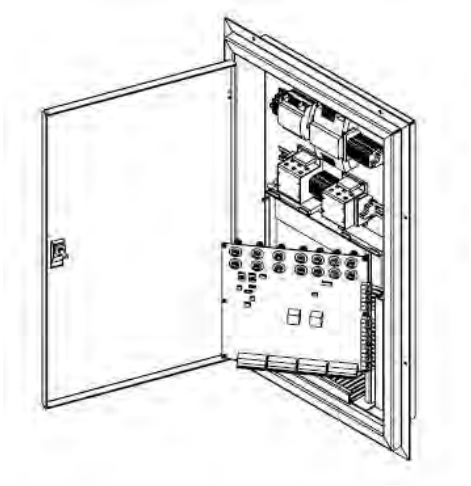


**Figure 12. New Control Box**

In order to organize the inside of the GrIP and consolidate all of the devices necessary for the control of the unit, a new enclosure was designed to house all of these components. The upgraded Rev. B boards were made operational with the testing of the entire system, and tested with the PCP GrIPs to the capacity of the lab (1MW - 1,200A). Design changes were also made to the GrIP, including cost reduction modifications that reduced the cost of the GrIP by about 10%.

Q2 2013 saw the completion of the layout of the PPP GrIP, see Figure 13, and mechanical manufacturing drawings were approximately 80% complete, see Figure 14. The first long-lead time components were ordered.

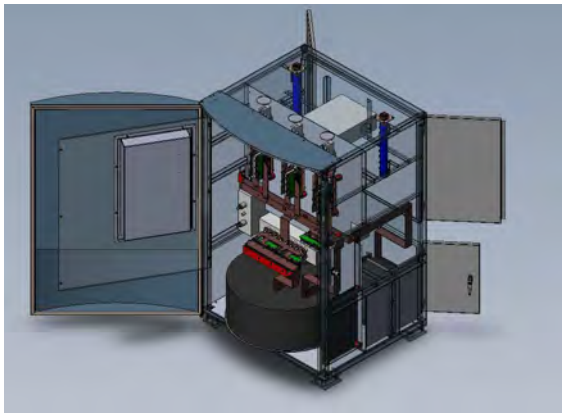


**Figure 13. PPP GrIP Solidworks Model**

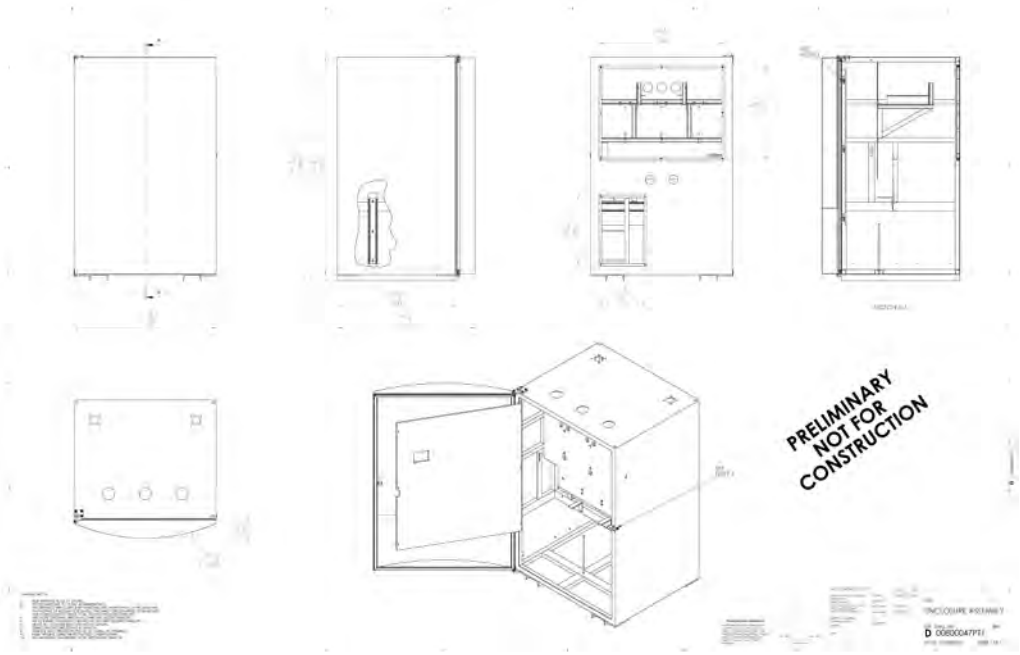



Figure 14. Initial set of mechanical drawings

Late Q3, after several versions of the PPP GrIP design, the final design was released and quoted for manufacture, see Figure 15.

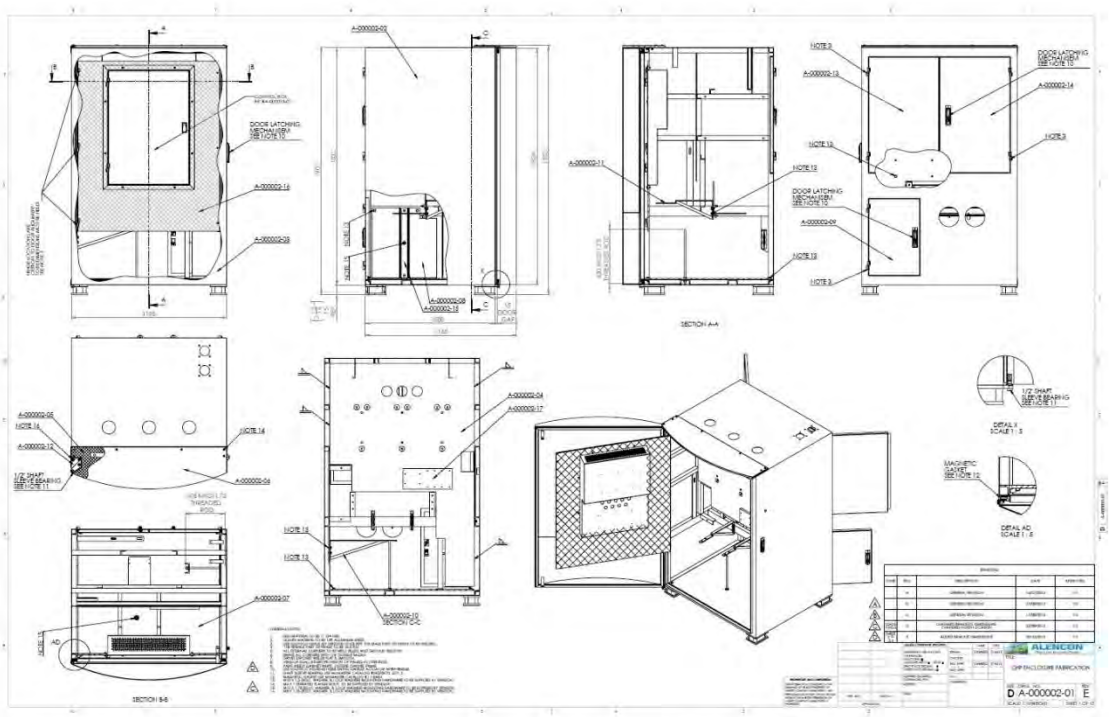


Figure 15. Final Manufacturing Drawings

By Q4 all outstanding components for the PPP GrIP had been received and were ready for manufacturing phase.

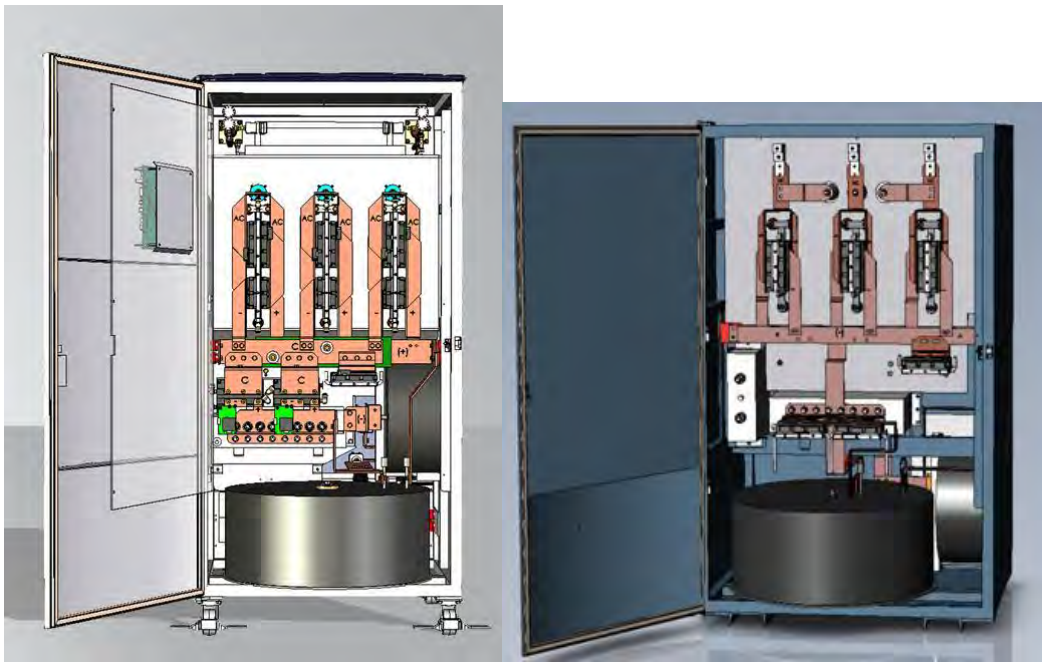


**Figure 16. PCP vs. PPP GrIP design**

Figure 16 compares the PCP design and the PPP design. Improvements included a reduction in the number of power components, larger spacing for easier maintenance, simplification of the enclosure, and an updated design for higher voltage components. The changes when moving from PCP to PPP Design are listed below.

- Reworked busbar for easier manufacturing and installation
- Moved the location of output to allow for easy connection to AC transformer
- Separated electrical and water to protect power electronics from water leaks
- Changed location of small choke for easier installation
- Updated capacitor location for easier mounting
- Optimized wiring and controls locations for easier installation and maintenance
- Updated heat sink and IGBT use for higher voltages and efficiency
- Removed wheels for easier mounting

| | PCP GrIP | PPP GrIP |
|---|---|---|
| DC Voltage | 750V | 2500V |
| Input Current | 500A (testable) 1000A (theoretical) | 1000A |
| Power Components | 23 | 17 |
| Weight | 4200lb | 4100lb |

### *5.2.1.2. SubTask 5.2: GrIP Modeling & Analysis*

Once models were created for the entire inverter system, the Matlab inverter system models were verified via testing, see Figure 17 and Figure 18.

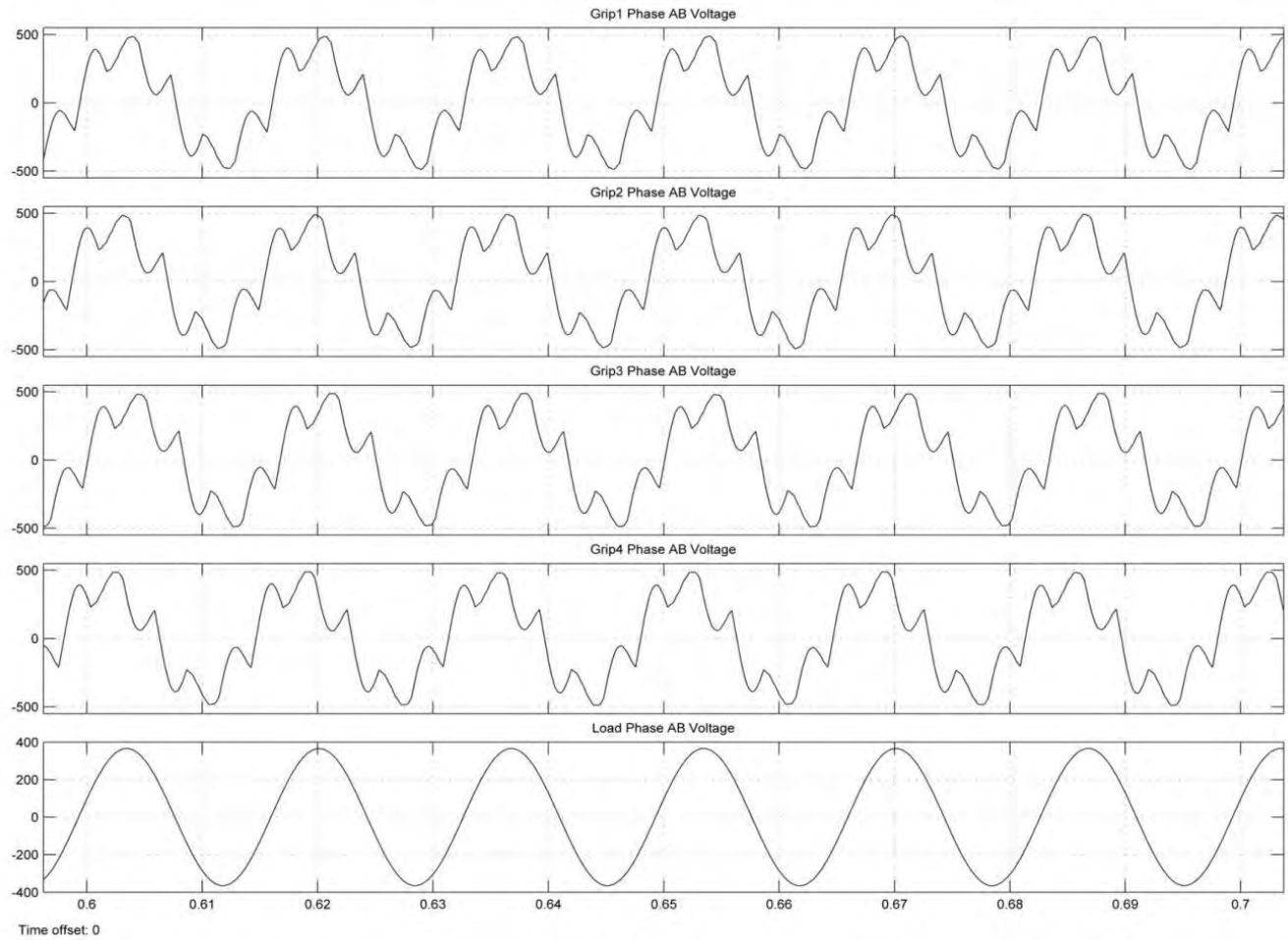



**Figure 17. Simulated Output of Four Units and the Output at the Load**

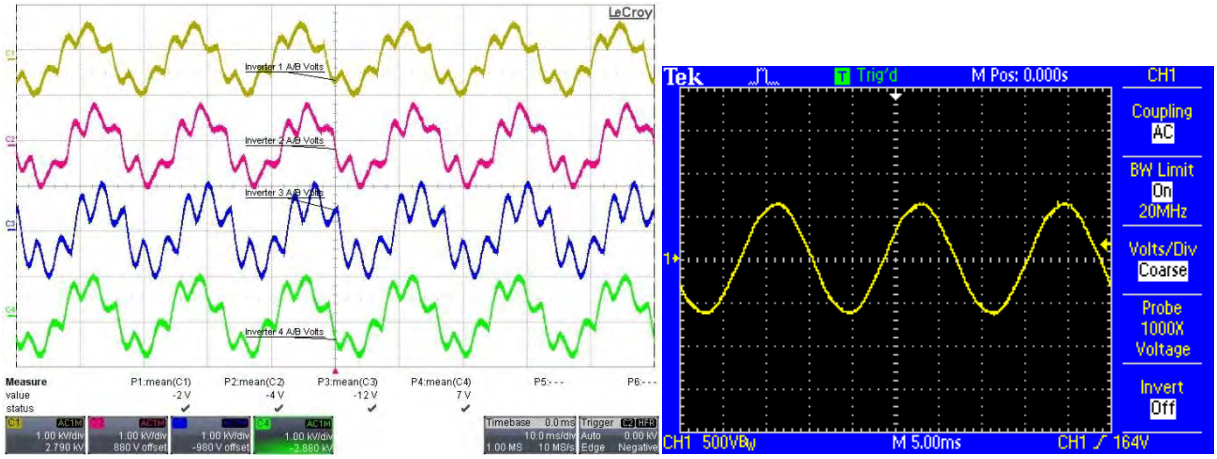



**Figure 18. Measured Output Voltages of Four Units and the Load**

Modeling and testing of the GrIP modules continued throughout the project, and provided a wealth of useful information. Models for the individual portions of the system were all completed, and the combination of these separate portions was under way by the end of Q1. Basic simulations for the controls, began with a static load model.

A simulation for the recirculation setup in the power lab was created in Q2, and various control schemes for the stable operation of the inverter system as a whole were tested within that environment. Basic simulations of the entire Alencon system, including PV, have begun and controls were continued to be modeled based on the accompanying results.

Several simulations were created and analyzed throughout the fourth quarter in 2013, including the modeling of the inverter system with SPOT devices, modeling of an inverter system with focus on the THD, the effects of filter capacitors on the perceived reactive power at the utility interconnection, various setups in the power lab, and more.

Figure 19 shows the single line diagram of the model for simulating the recirculation of power in the lab. This includes the transformers, rectifiers, inverters and load that are to be used. That is, the generated power is fed back to the input as a source and only power losses are supplied through the grid. Modeling was completed at all of the different voltage levels available in the lab, namely 650VAC, 1300VAC, and 1950VAC. The operation at all voltages was shown to be conducive to the testing that would need to be done.

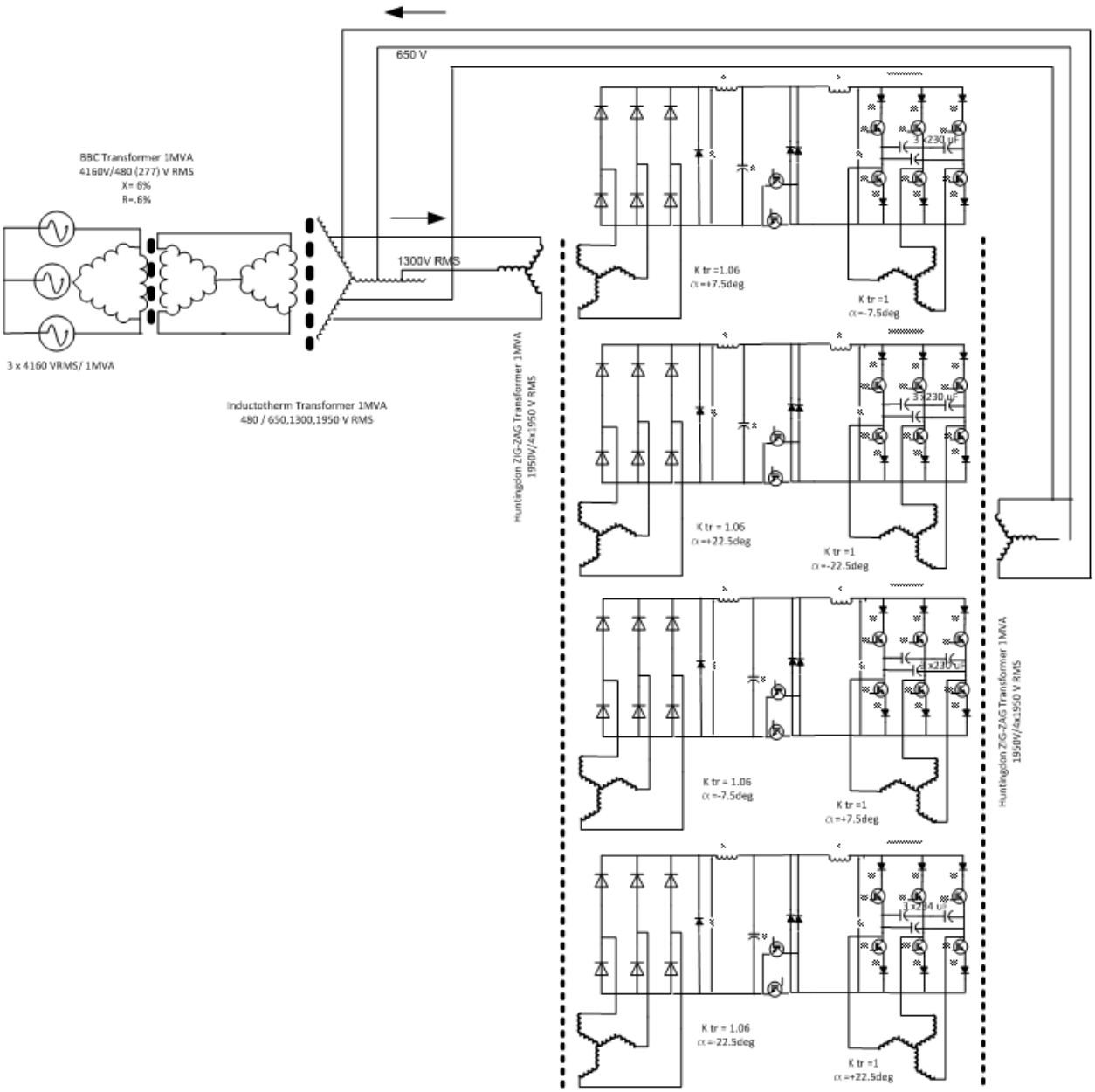



**Figure 19. Recirculation Test Setup**

### *5.2.1.3. SubTask 5.3: Build and Test PPP GrIPs*

Once the second revision control board hardware were tested and installed in the units, the full inverter system was tested with four units to the maximum capacity of the lab (1MW - 1200A) with remote control capabilities, see Figure 20.

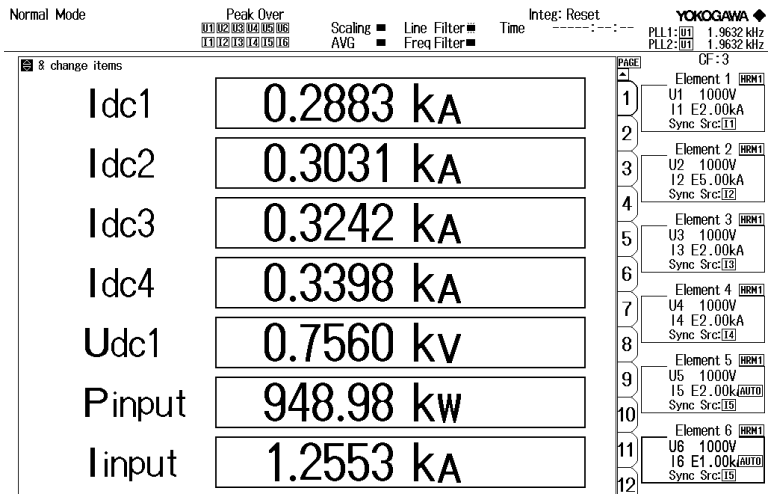



**Figure 20. Power Analyzer Readings for 1MW test**

Control doors on the existing PCP GrIPs were updated to be included in the PPP design, and the first of these were manufactured. Three more followed and all the PCP GrIPs were upgraded to utilize them, with feedback from their use being included in the PPP design, see Figure 22.

In Q2 2013, all of the controls were rewired to include the new control enclosure, including ethernet over fiber, and power was successfully run with the upgraded units. The single rectifier previously used for testing was found to cause serious distortions on the line (THD>30%) that hampered the synchronization and controls on the GrIPs which used the AC voltage as a reference. A multi-pulse rectifier was therefore designed and installed in the lab to reduce distortion on the line. This included four individual rectifiers, see Figure 21, and a phase shifting transformer.

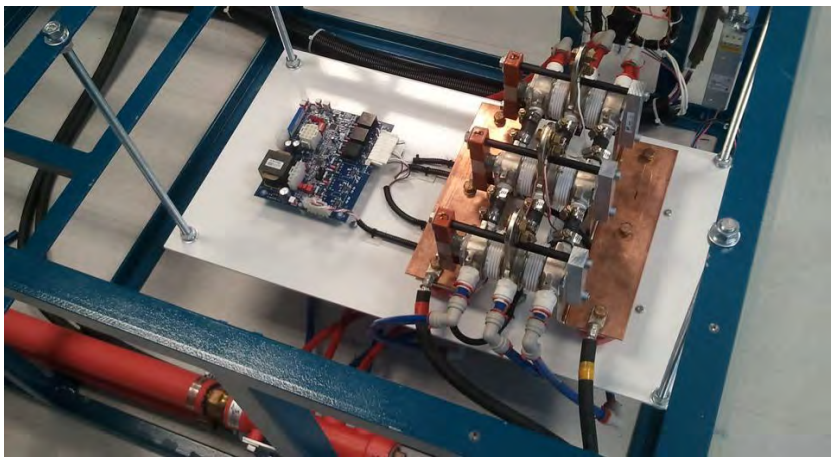


**Figure 21. Individual Rectifier**

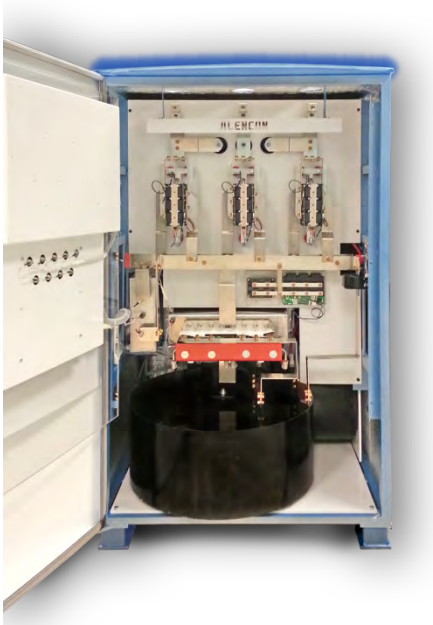
Figure 22. Rewired PCP GrIP

Any communications issues that were present previously were completely eliminated with the revision B boards that included the ethernet over fiber. Communications became far more robust thanks to the complete noise immunity of the fiber, and sensing required less filtering due to the optimized control enclosure and more optimal routing of harnesses, benefitting performance tremendously.

The third quarter of 2013 saw the beginning of PPP manufacturing, with the enclosure being the major bottle neck. In preparation of the new units, wiring harnesses were created for the new GrIPs in advance. All PCP Units were completely rewired, and a full 1MW test with four rectifiers and four inverters was completed. Alencon received the chokes, capacitors, and a majority of bus bar for the PPP GrIPs.

Over the course of the fourth quarter, Alencon received the enclosures from the fabricator and began assembly, see Figure 23. After minor modifications all four units were complete and ready for testing. Individual testing and burn-in of the units commenced at low voltage (800 Vdc). The new units would finally be able to operate at full voltage, to complete the second portion of testing.

Figure 23. Partially assembled PPP GrIP



PCP PPP

Figure 24. Comparison of PCP and PPP GrIP

Figure 24 and provides a comparison of the PCP GrIP and PPP units, and makes clear the advances that were made with the new design. A slightly wider and shorter enclosure with ample room for tools, the removal of the wheels and introduction of an easy-pick bottom, completely shielded enclosure for controls, optimized component placing, updating busing, etc., all added to what could confidently be called the pre-production prototype. Though some updates would follow, testing of the individual units had already begun by the end of the year, with higher voltage testing to commence the next year after some modifications to the lab setup.

Calorimetric testing of the GrIP also produced very promising results with great accuracy. Since measuring 1% losses would require extremely accurate test equipment, measuring losses rather than input and output power is far better. Within the GrIP, this is easy to do as all losses are already extracted through the liquid cooling system. This means that simply measuring the water flow and temperature rise of water in the system is enough to very accurately calculate the losses. Doing these tests confirmed previous simulations about the efficiency of the inverter, reaching 99.5% at its peak.

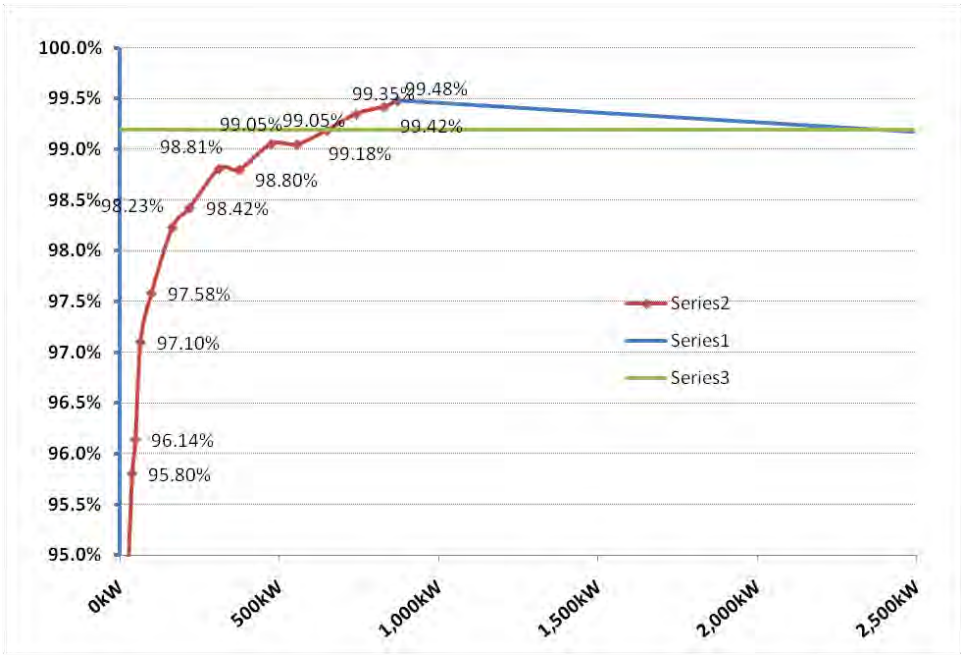



**Figure 25. GrIP Efficiency Curve (Measured - Series 2, Extrapolated - Series 1, CEC weighted - Series 3)**

### *5.2.1.4. SubTask 5.4: Begin Equipment Certification*

More detailed study of the UL & IEEE certification requirements were studied throughout the remainder of the project, and the selected certifying agency was approached once the final PPP GrIP design is complete. An agreement was put in place to begin the preliminary design review of the GrIP with the completion of the PPP design.

By the end of Q3 2013, the company had successfully completed a preliminary review with UL for the GrIP module. A plan of action and estimates for continued work with UL followed, and a member of the

team joined observer status for UL 1741 and IEEE 1547, setting a place in line for participation in the Standards Technical Panels and workgroup.

Since the UL preliminary review, Q4 brought updates that needed to be made to the design of the unit. Involvement has also begun with the IEEE 1547 workgroup, where among other things, updates were being made to the test procedures (1547.1a) and the overall scope of the standard (1547a) to eliminate gray areas and expand the applicability of the standard for systems in the US and around the world.

Simulations and modeling were completed on some aspects of the IEEE 1547 testing that were going to be needed, which were critical in understanding the type of equipment that would need to be added to the lab to ensure valid testing capabilities. This included the capacitive load needed for the anti-islanding test -- one of the more complex test setups required by the standard.

### 5.2.2. Task 6.0: SPOT PPP

Work in task 6 focused on the creation of the PPP SPOT. It was broken down into the design, modeling, construction and testing of the new devices.

#### *5.2.2.1. SubTask 6.1: Complete PPP SPOT design*

With the limitations of the silicon based IGBTs and mosfets at higher frequencies or voltages, it was determined that the SPOT would need to utilize newer Silicon-Carbide semiconductors to successfully operate at the voltages and frequencies required.

The auxiliary power supply circuit, PCB layout for the voltage booster, and the full bridge DC/DC converters utilizing Silicon-Carbide switching devices was completed in the first two quarters of 2013. PCB design for the SPOT mesh network communications hardware was also begun. All components were selected and purchased for the first test units, and the basic communication software was implemented for testing.

Improvements on the SPOT design continued, both from a controls and hardware perspective.

The second iteration of the SPOT PCB was assembled, including voltage booster and full bridge inverter. The next iteration of the SPOT breadboard was specified, including auxiliary power supply, booster, DC-to DC converter and microprocessor controls, and the next iteration of the control board was being implemented by the end of Q2.

The third revision SPOT was designated as the PPP design in Q3, and the layouts for control and power boards were finalized.

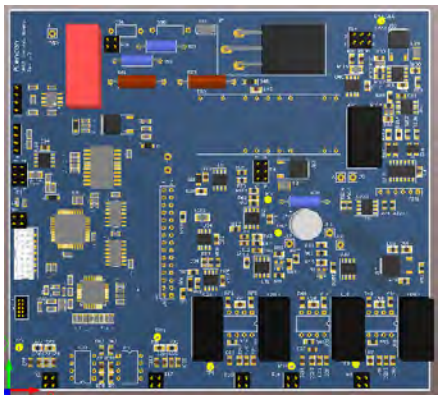


Figure 26. SPOT PPP Control Board

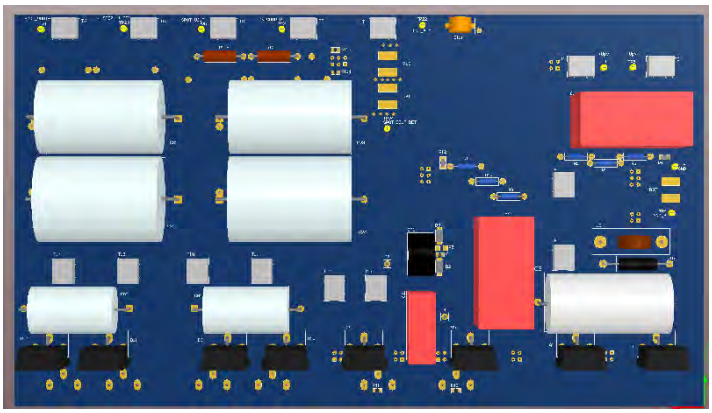


Figure 27. SPOT Power Board

In the fourth quarter, after the construction of three generations of the bench-top prototypes, a working pre-production prototype that met the project objectives was completed. With an operating frequency above 100kHz, magnetic components, and therefore costs, could be significantly reduced. This progress was only possible due to the new silicon carbide transistors that had been introduced only in January 2013. With these transistors, the required voltage, power, and frequency needed for the SPOT implementation would all become achievable. String controllers communicated with the system computer via a small RF transceiver board.

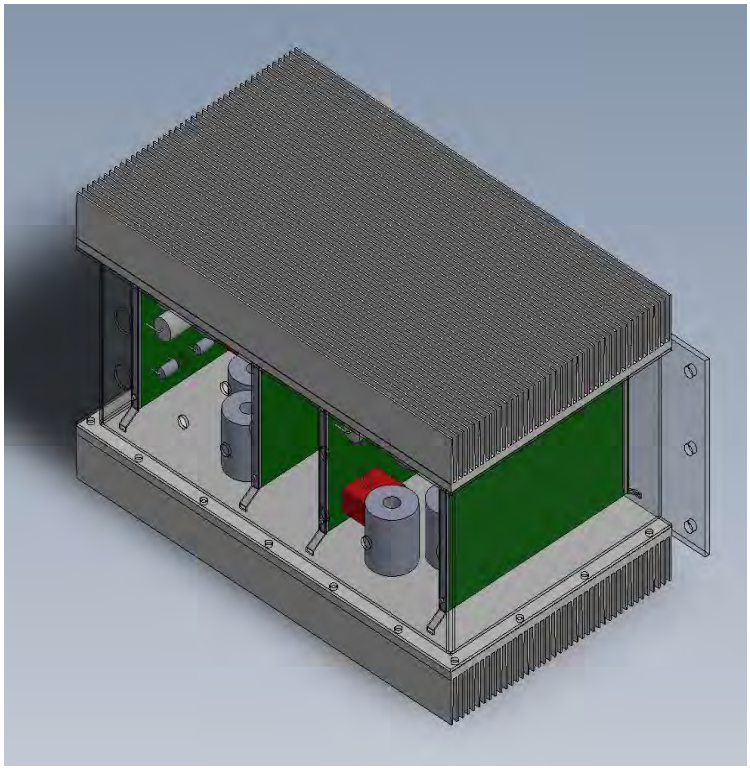


Figure 28. PPP SPOT Design

Besides the power electronics and controls portions of the project, the enclosure for the SPOT, heatsink design and packaging were also in full swing. The PPP SPOT design already provided a strong and compact means for combining the four string boards in one enclosure. Figure 28 shows the first model of the SPOT packaging design.

#### *5.2.2.2. SubTask 6.2: SPOT Device Modeling and Simulation (Multiple SPOT Devices)*

This task was to extend the Phase 1 SPOT model to simulate the operations of a full system of SPOT devices. By Q1 2013 detailed simulations were created for the Voltage Booster, DC/DC Converter, Fly-back Auxiliary Power Supply, "bang-bang" control of the smart load, and the first MPPT algorithm. All of these were tested under varying loads and conditions, some of which were part of the overall system testing. Simulations showed that the Voltage Booster and full bridge DC/DC converter would need to operate in the frequency range of 80 to 120 kHz, to maintain the required 2,500V DC for the GrIP input requirements. All models were based on the actual transistors used and parameters of real magnetic components.

In Q2 2013 a MathCad program was developed to determine optimal component parameters for the initial SPOT boost-converter (to be eliminated later on), including the design of the inductor and the estimation of losses in major components. The results closely matched measurements on the real board. Another program for the design of high frequency ferrite inductors and transformers for the DC/DC converter was also created. Simulations were created for the full-bridge SPOT inverter, and models verified operational waveforms and controls.

Extensive simulations and modeling of the SPOT PPP design were completed in Q3, along with multiple MPPT algorithms to be used with the hardware.

For most of Q4, modeling was done on the combination of the inverter and harvesting systems. Due to the large number of SPOTs in a standard 10MW system, and therefore the large number of components and controls throughout, it was not possible to simulate a system in its entirety.

This figure has been omitted for confidentiality reasons.

**Figure 29. Super SPOT**

Therefore a model of a "super SPOT" was created to emulate the operation of several combined SPOTs, without the additional computational strain of modeling hundreds or thousands of SPOTs in one system, see Figure 29. This allowed for testing of different control schemes on both the harvesting and inverter systems, and the analysis of transient effects, insolation changes, etc.

#### *5.2.2.3. SubTask 6.3: Build PPP SPOTs*

The first revisions of some of the SPOT boards were made and underwent testing in Q1 2013. Specifications for their final design evolved out of everything learned in the process. Designs were created and implemented for a full bridge, half bridge, and boost converter SPOT, with development focus mostly on the boost converter at the time.

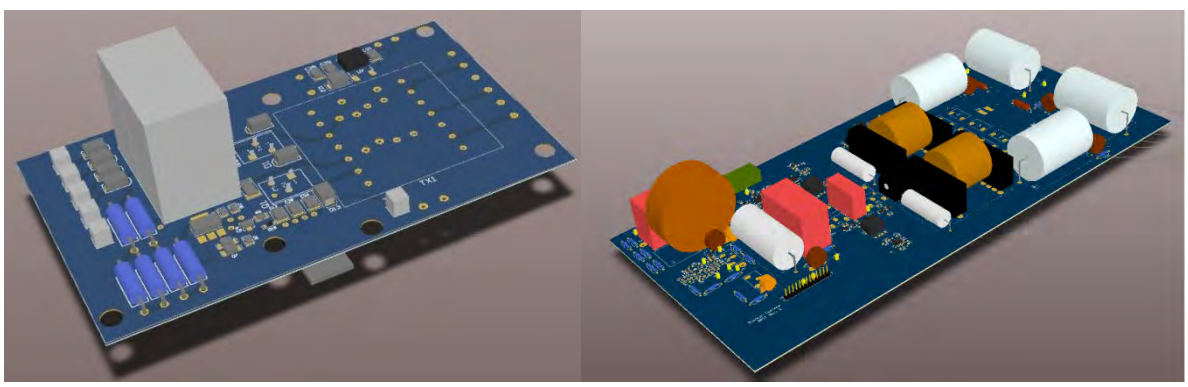


**Figure 30. Aux Power Supply and Boost Converter / Full Bridge Designs**

Through the second quarter of 2013, the board level auxiliary supply for the controls, drivers and measurement circuits were completed. Basic controls were implemented using a Freescale Kinetis microcontroller evaluation board, booster circuit was built. Several prototype RF communication boards were also created for testing purposes.

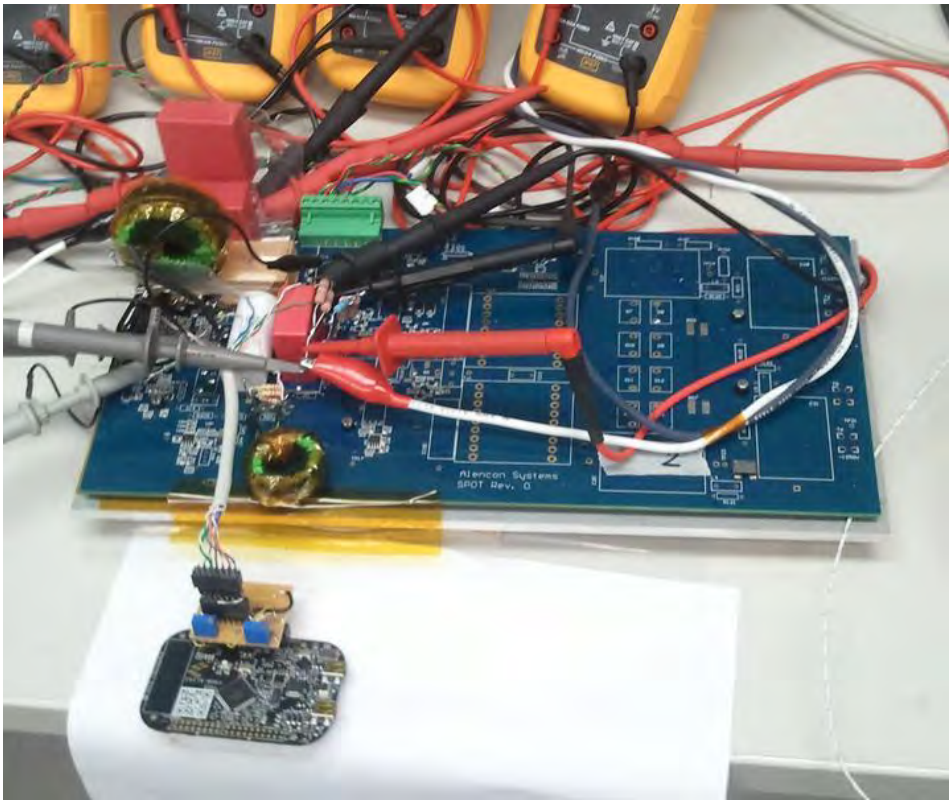



**Figure 31. SPOT and controls prototypes**

The first of several PPP SPOTs was assembled in Q3, with a second set of boards to be completed by Q4. Both the V3 SPOT PCB Design and assembly were finished in record time (~1.5 weeks).

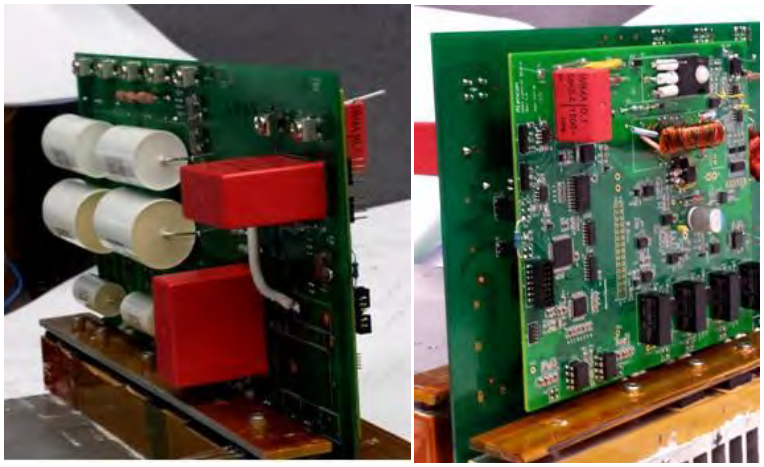


**Figure 32. Constructed PPP SPOT**

The PPP SPOT prototypes were built by the end of Q4, with the magnetic portion of the system consisting of two transformers, connected in parallel, to deliver about 5kW to the load, as shown in Figure 32. The default resonance tank elements were Lr = XX uH and Cr = XXnF. System variables, including input current and efficiency, were evaluated on a range of frequencies for this tank selection.

The DC/DC converter was implemented as two power and control boards sandwiched together as shown in Figure 32.

This figure has been omitted for confidentiality reasons.

**Figure 33. SPOT Schematic diagram of a String Controller circuit for delivering full power of 5kW**

**Figure 34. SPOT PV String Controller delivering full power of 5kW**

### *5.2.2.4. SubTask 6.4 Test PPP SPOT operation*

The first quarter 2013 focused on only basic board level testing on the assembled PCB boards. By Q2 2013, the upgraded SPOT test station included a 5.4kW resistive load, enabling the testing of the SPOTs to that power level.

Figure 35. Resistive Load

Testing continued with each sub-section of the PCB at a time. The booster circuit was proven effective and functional, leaving only the continued tuning of the magnetic components, which then accounted for the largest portion of losses within the booster. This gave great promise to reaching 99% or greater efficiencies in the SPOT. In Q3, the PPP SPOT was tested to 4.4kW, with higher power and voltage testing to come thereafter. Alencon began recording efficiencies for the different magnetics and board configurations, reaching a SPOT booster circuit efficiency at 3kW of 98.6% with optimizations on the magnetics still to come. Power losses in the transistors were found to be very low - less than 0.5%. Discussions had also begun with the landlord to install a 25 kW test PV system on the roof.

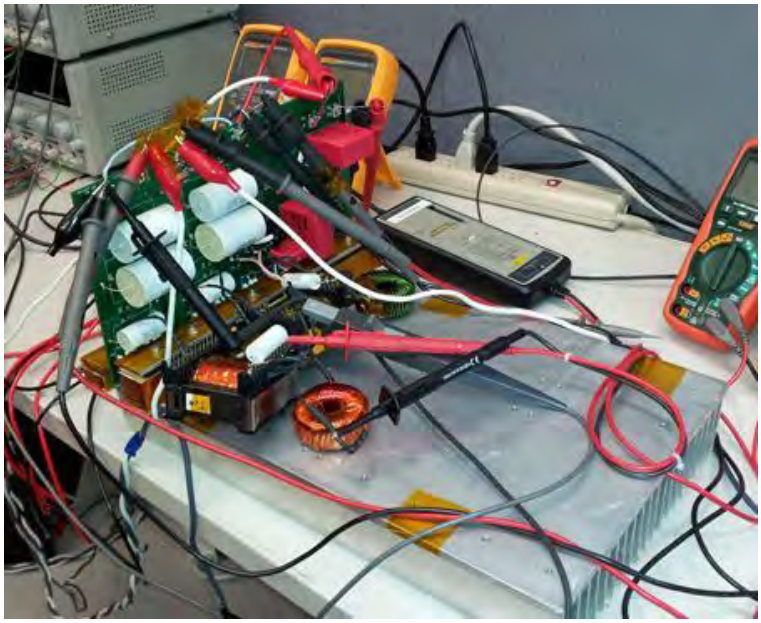


Figure 36. SPOT PPP under testing

Finally in Q4, two types of tests were done with the PPP SPOT: one for efficiency and one for frequency response.

Efficiency testing was used to verify proper operation and the effectiveness of the circuit topology, while frequency response tests verified the operation of the SPOT and its capability to variably load the string of modules. This demonstrated its ability to do Maximum Power Point Tracking (MPPT).

Figure 37. SPOT Resistive Load Setup

The output power was controlled by varying the operating frequency of the PV string controller. Waveforms for the operating frequencies of 105 kHz and 110 kHz are shown in the Figures 9 and 10 respectively. Pink and yellow lines give the gate drive commands, blue the capacitor voltage, and green the inductor current. Based on the waveforms, it is clear that at 105 kHz the unit is operating near resonance, as the inductor current already hits zero before the next switching cycle. The 110 kHz waveform shows that operation of the unit at this frequency is above resonance.

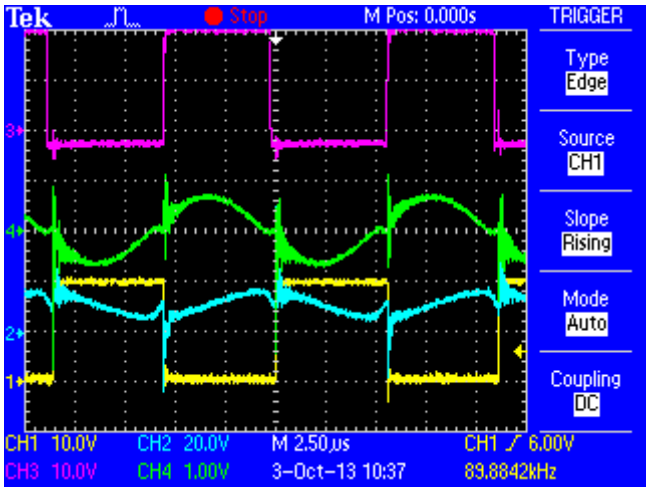



Figure 38. Waveforms for the operating frequency of 90kHz

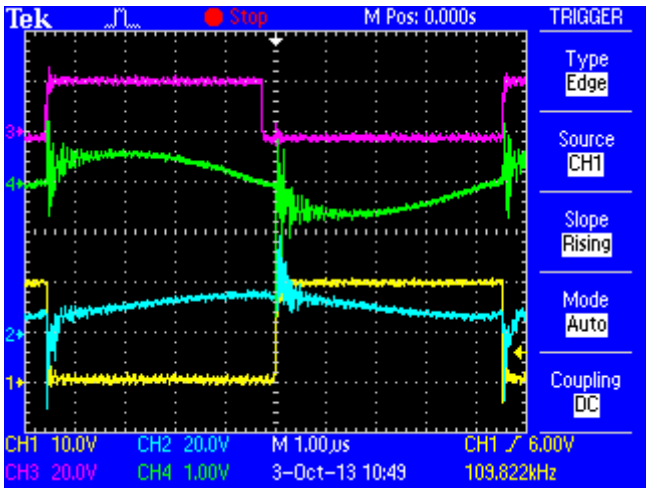



Figure 39. Waveforms for the operating frequency of 110kHz Frequency Sweep

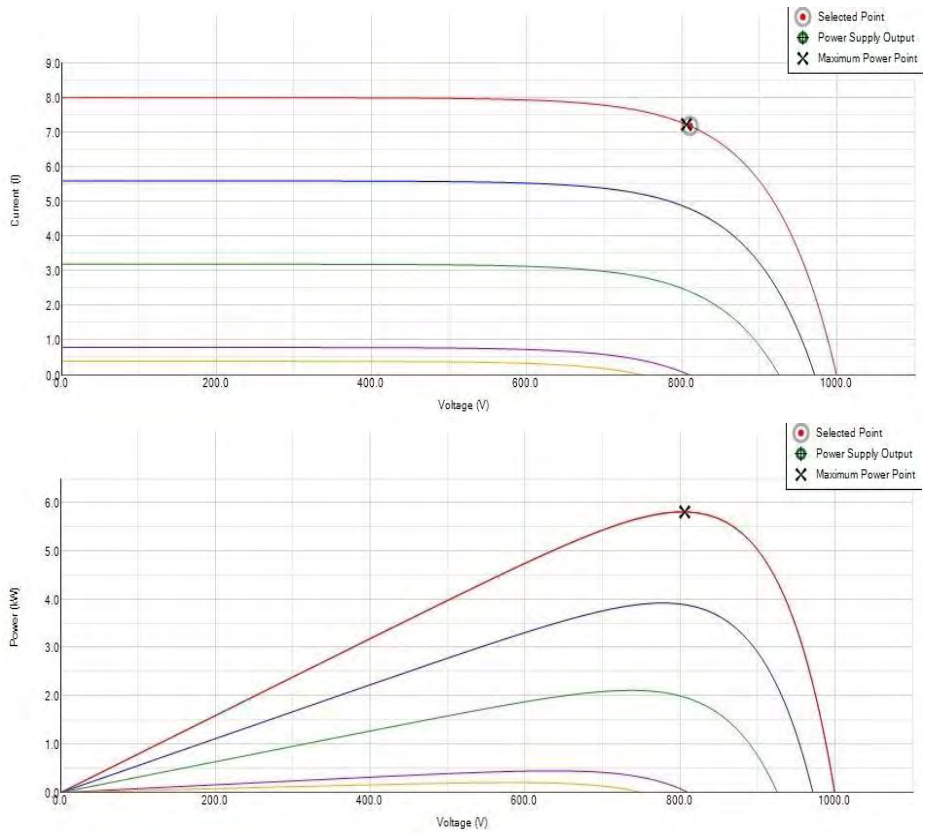



**Figure 40. MPPT Curves and operating points**

### 5.2.3. Task 7.0: System Integration

Complete consolidation and modeling of overall system and controls. Begin integration of the Alencon system including harvesting, conversion and SCADA sub-systems.

Each subsystem was broken into a set of milestones that reflected testable configurations of a set or subset of features required of the completed subsystem component. Each of these milestones was internally broken down into a set of work items which were individually tested by the engineer responsible for implementation. For each testable configuration, a test plan was carried out under the supervision of the lead software and hardware engineers. When testing of a configuration was complete, work began on the next testable configuration in the development path. Configurations that implemented a full enough feature set to be tested in conjunction with other subsystems are referred to as *baselines*. The lists of development baselines for each subsystem are summarized in the tables that follow.

**Table 1. SMC Baselines**

| Baseline Name | Description |
|---|---|
| SMC R0 | Proof of concept software. Manual controls via UDP. |
| SMC R1 | DDS communications implementation. Semi-Automated Controls. |
| SMC R2 | Automated system configuration and calibration from deployed system setup file. |

**Table 2. GrIP Baselines**

| Baseline Name | Description |
|---|---|
| GrIP R0 | Proof of Concept Prototype Baseline. Manual controls via PC Application. |
| GrIP R1 | Pre-Production Prototype framework including Real Time Operating System and addition of external SDRAM. |
| GrIP R2 | Pre-production software with full DDS communications. |
| GrIP R3 | Software port for production control board. Contactor controls needed for UL testing. |

**Table 3. SPOT Aggregator Baselines**

| Baseline Name | Description |
|---|---|
| SPOT Aggregator R0 | Software framework ported for target platform: RTOS, SDRAM Drivers, TCP/IP Stack, DDS Framework. |
| SPOT Aggregator R1 | DDS data model and communications for SPOT Aggregator. |
| SPOT Aggregator R2 | Mesh Communications with SPOT. Handshaking and data polling. |

**Table 4. SPOT Baselines**

| Baseline Name | Description |
|---|---|
| SPOT R0 | Implementation of sensing and DCDC converter controls. Manual user interface with VB Application. |

| | |
|---|---|
| SPOT R1 | MiWi communications with SPOT Aggregator. Handshaking and responses to data polling. |

**Table 5. System Monitor Baselines**

| Baseline Name | Description |
|---|---|
| Sysmon R0 | Manual GrIP control via UDP. Text file logging. |
| Sysmon R1 | Monitoring of GrIPs via DDS Text logging. |
| Sysmon R2 | GrIP Calibration and Configuration Interface. |
| Sysmon R3 | Monitoring of GrIPs via DDS. Secure WAN interface to VIEWS. High Speed Data Logging. |
| Sysmon R4 | Monitoring of GrIPs, SPOT Aggregators, and SPOTs via DDS. Secure WAN interface to VIEWS. High Speed Data Logging. |

**Table 6. VIEWS Baselines**

| Baseline Name | Description |
|---|---|
| VIEWS R0 | Limited diagnostics readouts for GrIPs. Local file interface with System Monitor. |
| VIEWS R1 | Extended diagnostics readouts for GrIPs. Real-time plots. |
| VIEWS R3 | Secure WAN interface with System Monitor for remote streaming of data. |

### *5.2.3.1. SubTask 7.1 Create and Model System Controls*

The first quarter of 2013 focused on creating "bang-bang" controls for the smart load and inverter current control, a timed voltage sweep MPPT algorithm, and a soft switching technique for the DC/DC converter. Individual controls for each subsystem were developed, simulated and applicable testing were conducted in the lab.

In the second quarter of 2013, system stability for the recirculation of power with a resistive and inductive load was modeled.

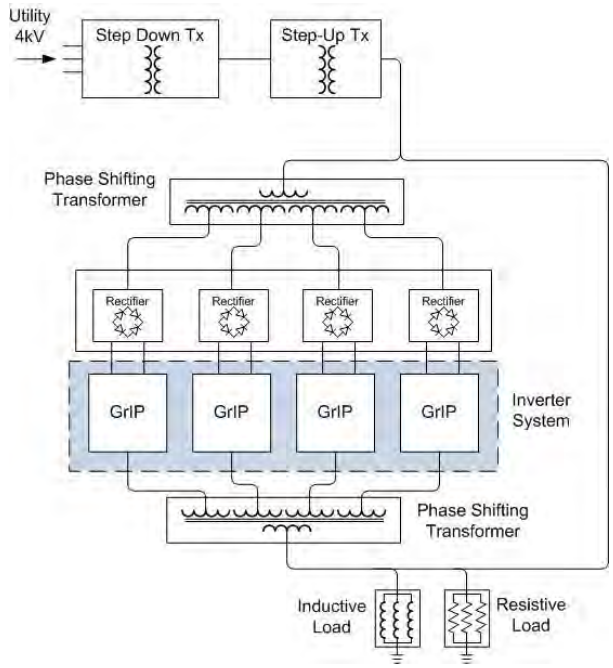



**Figure 41. Recirculation Model Setup**

Individual controls for each subsystem were developed, simulated, and applicable testing was conducted in the lab.

In the third quarter, local GrIP controls had been extensively modeled and simulated, including THD corrections with phase shift adjustments on a per-unit basis. SMC implementation started, with a three phase approach to the implementation by a consulting company.

Finally in Q4, the main orchestration of the inverter system, as well as the central tie-in for all other peripherals and sub-systems, was the System Master Controller (SMC). This device would be in charge of all communications and data acquisition to and from the GrIPs and SPOTs, while also handling the high level controls for the inverter system as a whole. This included monitoring the state of the utility interconnection to determine what, if anything, needed to be done to mitigate arising issues.

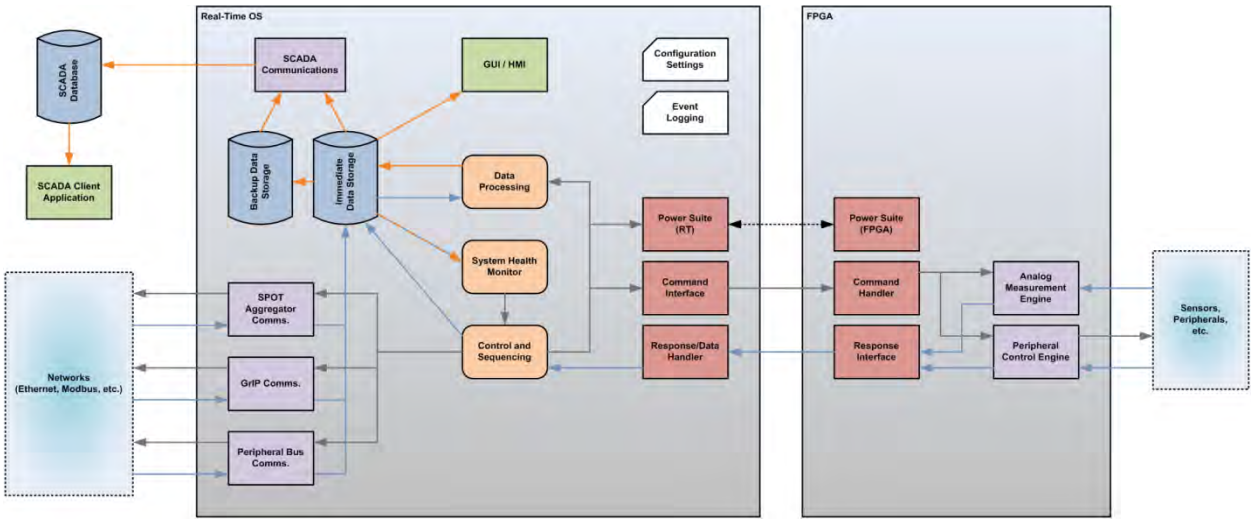



Figure 42. SMC Overview

The overview in Figure 42 shows the different modules that are to be implemented on the SMC. These range from communications interfaces, to data processing, as well as system health monitoring.

### *5.2.3.2. SubTask 7.2 Complete Communication System for SPOTs, GrIPs and SCADA*

In Q2 of 2013 the pre-production RF communication board was designed and tested with demo software to validate communications across several nodes. Development on the TCP/IP stack and fiber optic communications interface for the GrIPs was completed and tested successfully. GrIP controls were manually validated using the System Monitor application via a simple UDP based messaging protocol. A large portion of the functional specifications for the master controller were completed and work began to design the software architecture for the master controller subsystem.

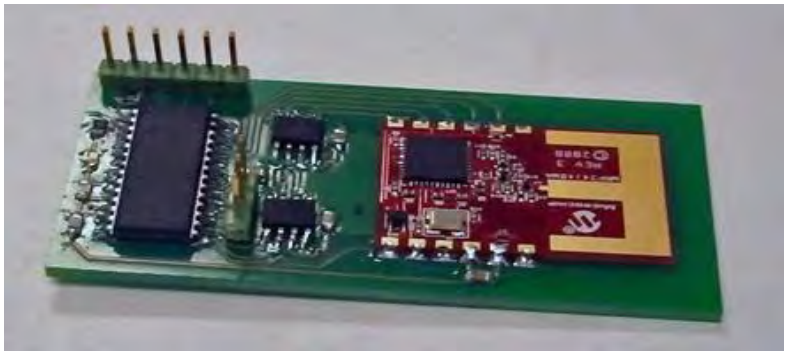


Figure 43. Wireless Communication Module for SPOT

In Q3 of 2013, Real-Time Innovations' Data Distribution Service middleware stack was selected as an off-the-shelf solution for the communications protocol. The protocol was selected to address reliability and scalability issues inherent to real-time distributed systems. The vendor choice was based on the wide number of supported platforms and tools which help to reduce development time and promote maintainable software. Rapid software prototyping was done to prove the concept for the system communications model. Shortly after, the initial system communications model was designed. Implementation of the DDS middleware stack for the GrIP target platform began at the end of the quarter.

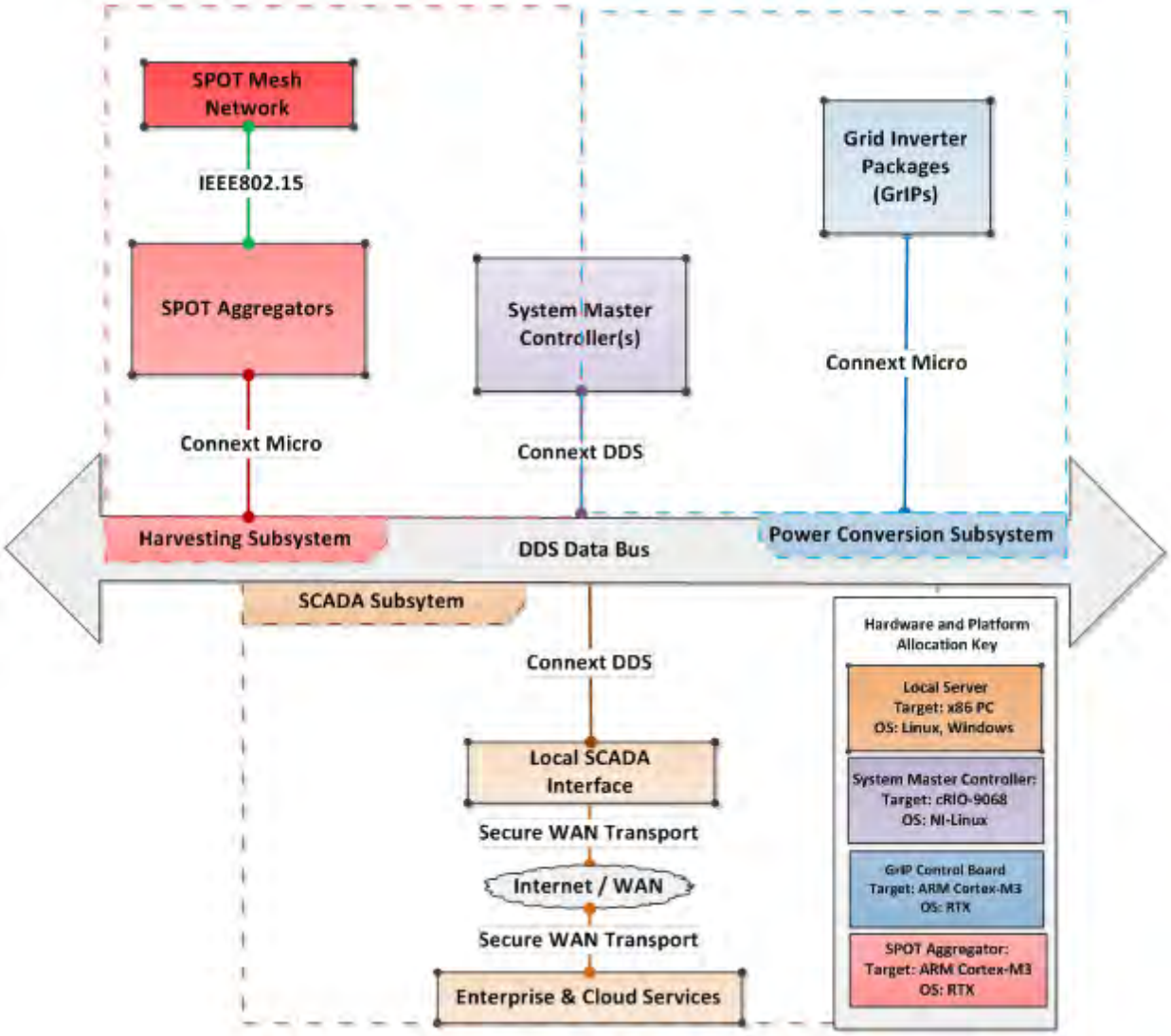



**Figure 44. The DDS protocol acts as a virtual data-bus for the system**

In Q4 of 2013 the physical network topology was designed with accommodations for redundant controllers and physical communications links. A top-level representation of the communications subsystems is shown in figures 42 and 43.

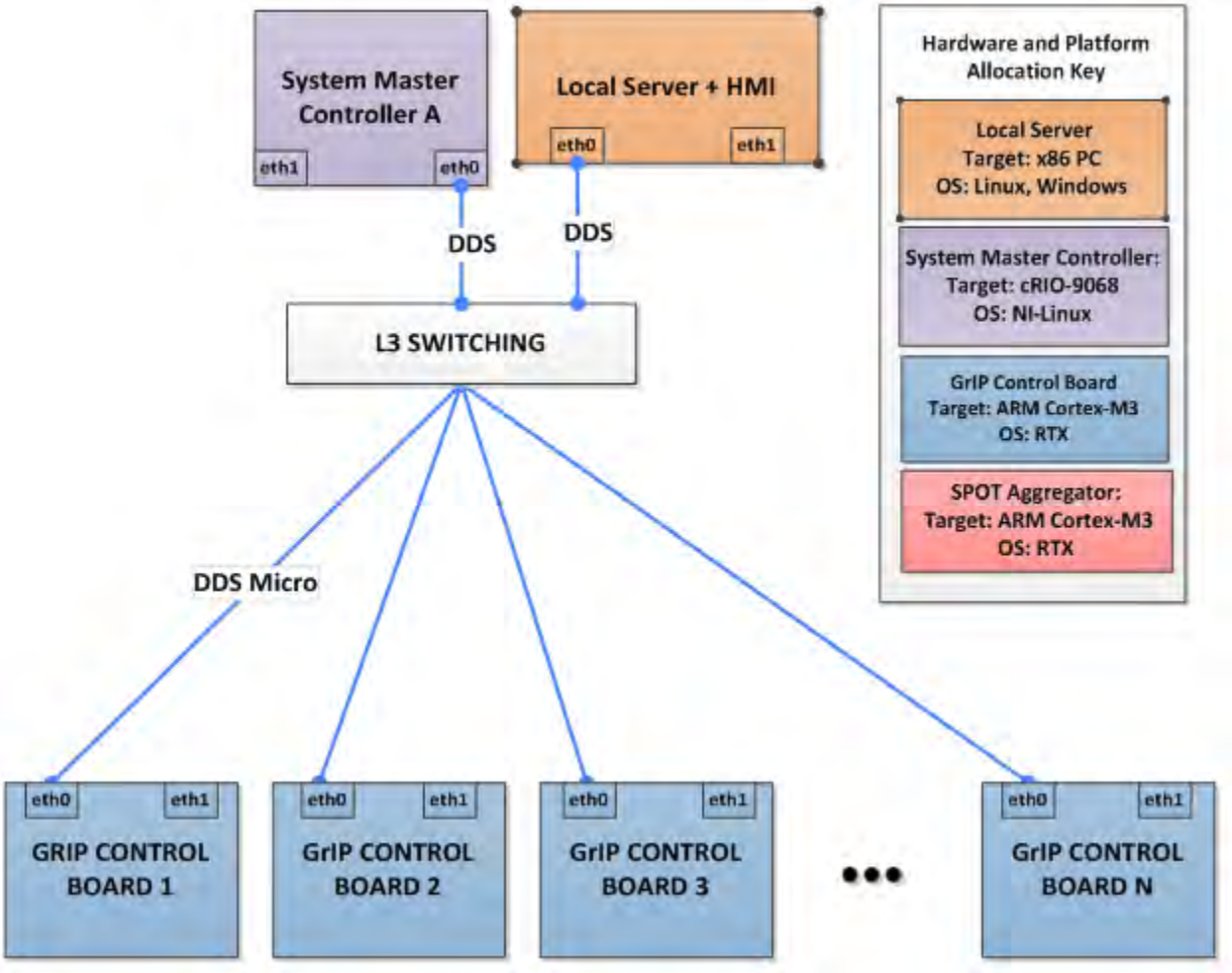



**Figure 45. Communications interfaces for the inverter and monitoring systems**

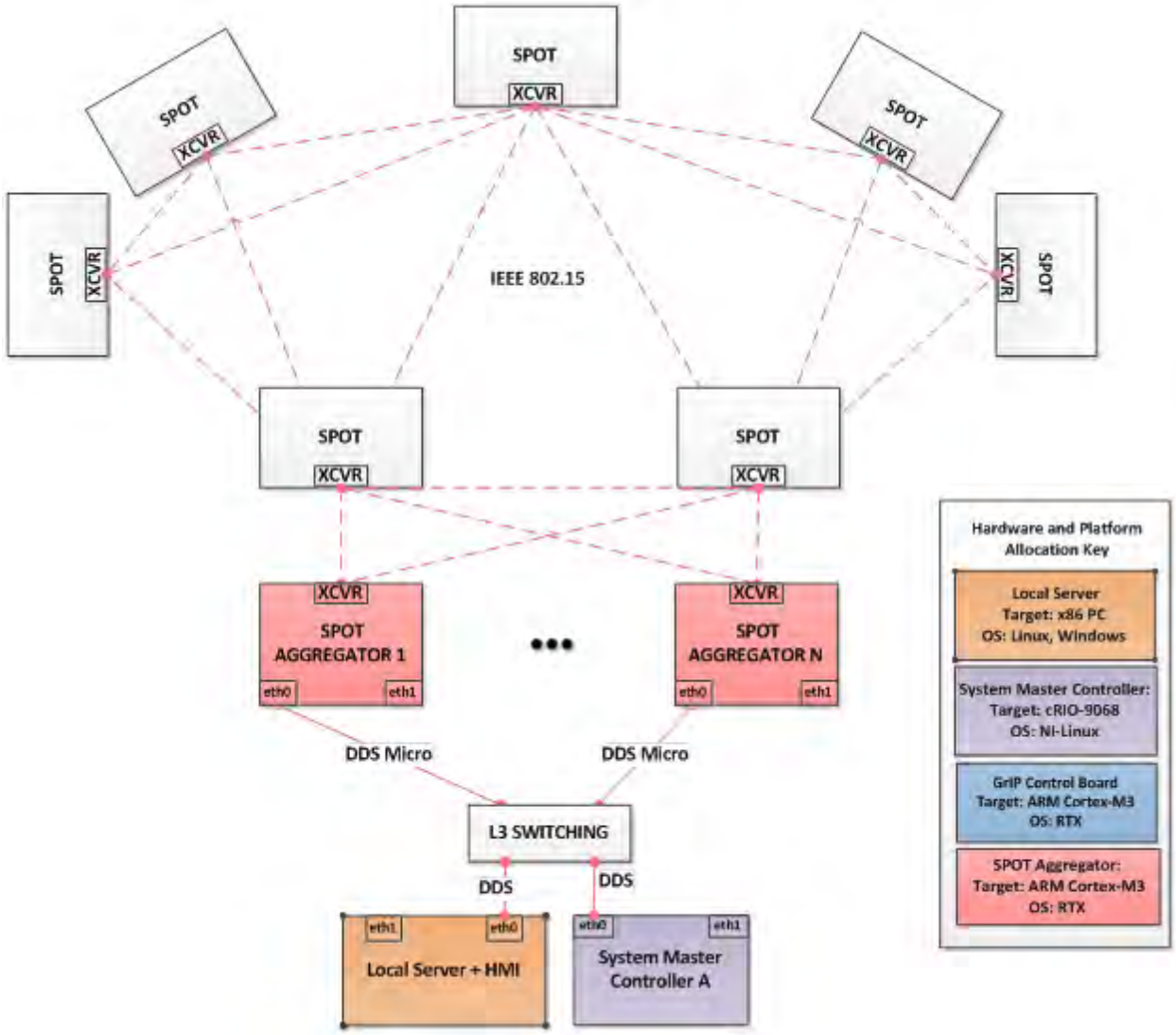



**Figure 46. Communications interfaces for the inverter and harvesting systems**

The top image in Figure 46 shows the direct connection, via ethernet over fiber, that the SMC utilizes to communicate to the individual inverters. In the bottom image, the harvesting communications subsystem with multiple aggregators can be seen. Throughput and scalability requirement estimates were created based on the most current system data-model. Cost of networking equipment in terms of dollars-per-watt of system production was also estimated.

#### *5.2.3.3. SubTask 7.3 Integrate harvesting and Conversion Systems*

In Q1 of 2013 a simulation of the entire system was modeled, utilizing PV modules, MPPT, DC/DC Converters, inverters connected to a load. This simulation was used repeatedly to validate the plans for system integration.

In Q3 2013 the first baseline of System Master Controller (SMC) was implemented utilizing the NI cRIO platform. Integration testing with the GrIP control boards began. A local logging engine was implemented to provide testing analytics.

#### *5.2.3.4. SubTask 7.4 Report on System Costs*

In Q1 of 2013 a preliminary BOM for the most current SPOT revision was completed. PCP GrIP Cost analysis was completed. PPP GrIP cost analysis began. Updates to the BOM and cost reductions were updated in the cost/pricing of the GrIP inverter system. As SPOT development continued, estimation of BOMs for the individual portions of the units began.

By Q2 of 2013 the GrIP PPP BOM was approximately 90% complete, with manufacturers for some minor components still being selected. The BOM for the SPOT included some initial estimates of costs. Initial targets for the SPOT were favorable compared to requirements.

In Q3 of 2013 an analysis of BOS system costs by Rowan University was completed, and was reviewed internally. Preliminary results were promising.

### 5.2.4. Task 8.0: PV System Engineering (Phase 2)

An important tool for Alencon in the commercialization of its products will be the creation of a beta site to demonstrate to customers. This will include the operation of multiple SPOTs in parallel, as well as the successful interconnection of the inverter system to a utility.

#### *5.2.4.1. SubTask 8.2 Beta Site PV System*

In Q1 2013, a meeting was set with the local utility and Alencon's landlord, to discuss the Alencon's plans to install a beta system on the roof of the complex. If this is successfully built, it will help in testing, provide credibility, and help the bankability of Alencon with potential customers. Discussions were then under way to determine if signing a power-purchase agreement (PPA) with the building owners would be the best solution. By Q2 2013, discussions with the landlord on structuring a PPA commenced, and a small 25kW system for SPOT testing purposes was installed on the roof.

At the turn of the third quarter, an agreement was finalized for the test site with the building owner. A preliminary design for the 400kW beta system was created, and quotes were received for the components (modules, racking, etc.) of the test system. A structural review was completed to ensure the roof would be able to withstand the load of the two PV systems.

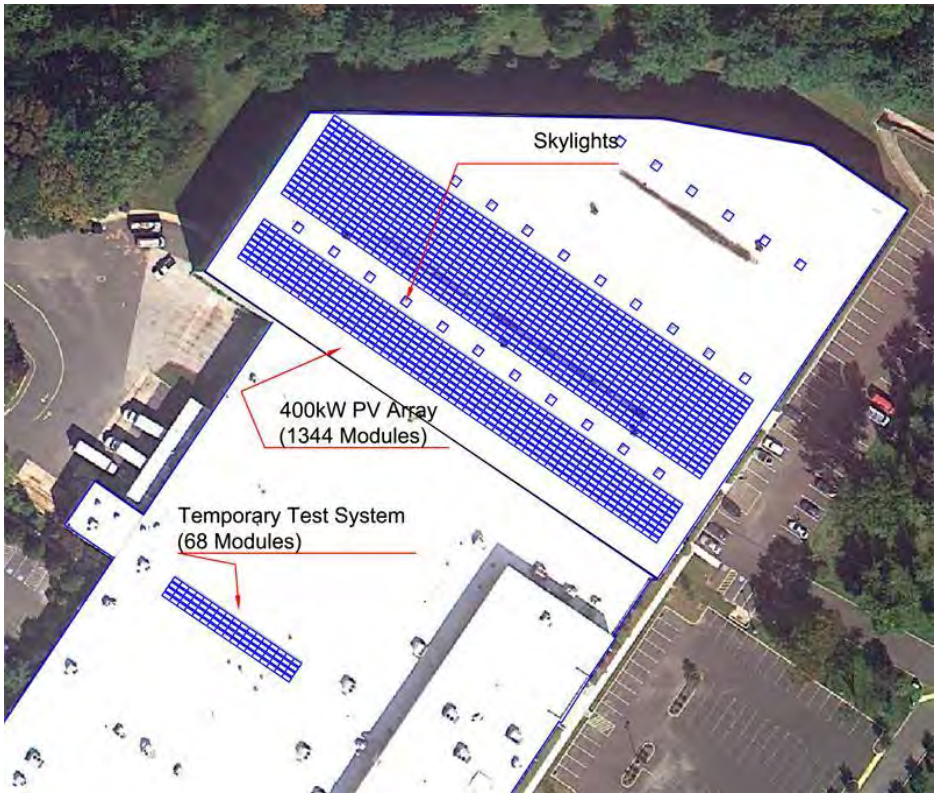



**Figure 47. Rooftop PV systems preliminary layouts**

With the details of the structural analysis of both the lower (40ft) and higher roof (70ft) coming to light in Q4, it was determined that the lower roof would not be capable of safely withstanding the additional load of a ballasted PV system. This meant the test system would have to be moved to the high roof, as well, see Figure 47.

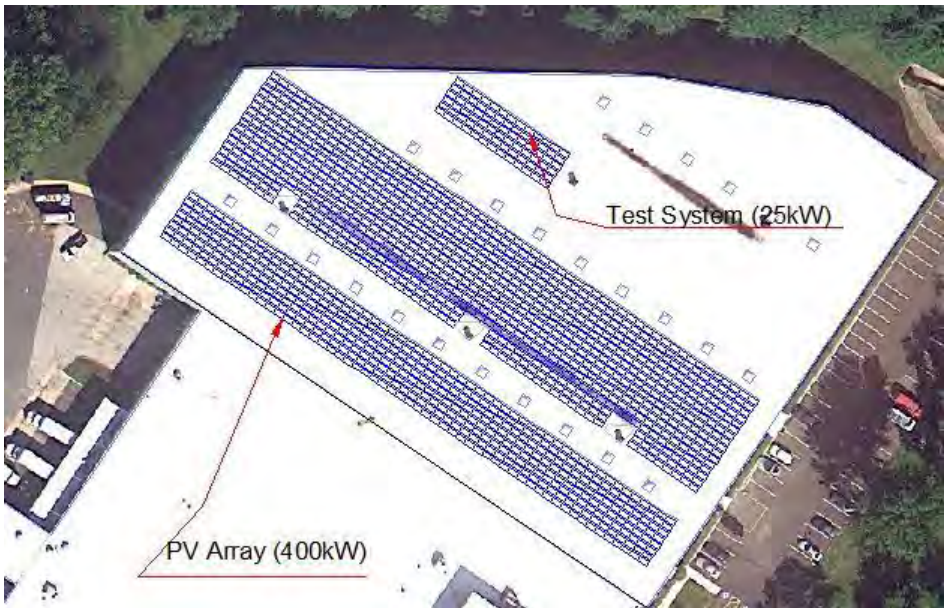



**Figure 48. Beta Site and Test PV system Locations**

Three entities have shown keen interest in investing in the beta site when it is completed. With the completion of the PPA agreement, one of these investors was chosen to partner with Alencon on the installation.

### 5.2.5. Task 9.0: Project Management and Reporting

The yearly audit was completed in April 2013, and updates were being made to the accounting and tracking system Alencon used to report to the DOE. All updates to the accounting and reporting system were completed by Q2, as requested in the yearly audit. The continuation application was completed and provided to the DOE, and finally a BP2 closeout presentation was held at the DOE offices in Washington D.C. Regular discussions and monthly presentations were held with technical leads.

## 5.3. Phase 3: Design Completion and Certification

### 5.3.1. Task 10.0: Inverter System Testing and Certification

One of the major tasks in the final phase of the project was to complete the inverter system, including the docking station, communications and controls, and move towards certifying the inverter system. This task was broken down into four subtasks: producing a safety analysis on the GrIP, complete the communication system hardware and software, complete the design of the dock, and certify the inverter system and its GrIPs.

#### *5.3.1.1. SubTask 10.1 Produce GrIP Safety Analysis*

As of Q1 2014, the fundamental safety features of the GrIP software were complete, allowing for corresponding controls on the SMC to be implemented. This allowed for the coordination of different GrIPs within the system, creating a uniform group from the independently operating modules. Requirements and specifications were updated accordingly. A user manual and safety analysis was subsequently completed.

Testing for UL1741 requires the testing of certain device failures within the system to ensure that such faults can safely be handled or that they do not affect the safety of the system. For this, in Q2 and Q3 of 2014, a detailed report of all of the failure modes of the applicable devices was written. Portions of this report were used in the complete safety analysis.

#### *5.3.1.2. SubTask 10.2 Communication System Hardware and Software*

The DDS integration with the GrIP application software was brought to completion in Q1 2014. Due to some issues with the previously selected TCP/IP stack that caused failures in the handling of fragmented packets, a new TCP/IP stack with packet fragmentation compatibility was developed in parallel to the finalization of the GrIP DDS application software. The new stack served as a direct replacement for the old and was swapped with minor investments in time.

The control board hardware was also updated to include a new, more reliable and robust fiber optic ethernet module. Communications hardware for the interconnection between the GrIPs, the SMC, and other network-connected devices was selected.

In Q2 2014, the DDS implementation on the GrIP was completed and deemed operable. While performance with respect to time was not designated a set goal, the slightly slower response time was not found to be an impediment to the operation of the system or any of the requirements for certifications. This included the new TCP/IP stack based on the open source lwIP, and was proven and tested to work with up to 50 GrIPs.

These performance issues were subsequently ironed out in Q3 2014, and the inverter system was found to be capable of providing sub-cycle command-response latencies. The multi-casting of messages and commands was then implemented, reducing required bandwidth. Finally, the DDS micro implementation on the GrIPs was updated to the newest software release.

### *5.3.1.3. SubTask 10.3 Complete Centralized Inverter Bus & Docking Stations*

The main task of the docking station / centralized inverter bus is the coupling of the harvesting and conversion portions of the Alencon System. The combination of separate systems gives some advantages that other topologies are not able to utilize. In this case, the addition of the DC/DC converter SPOT gives the advantage of being able to detect ground faults on the PV string side, which can be isolated due to the galvanic isolation of the SPOT itself, without requiring a system shutdown. Ground fault detection on the DC bus system is handled alongside that of the inverter. Additional sensing can also provide insight into what portion of the DC bus and inverter system has a ground fault and can help isolate it so the remainder of the system can continue to operate safely.

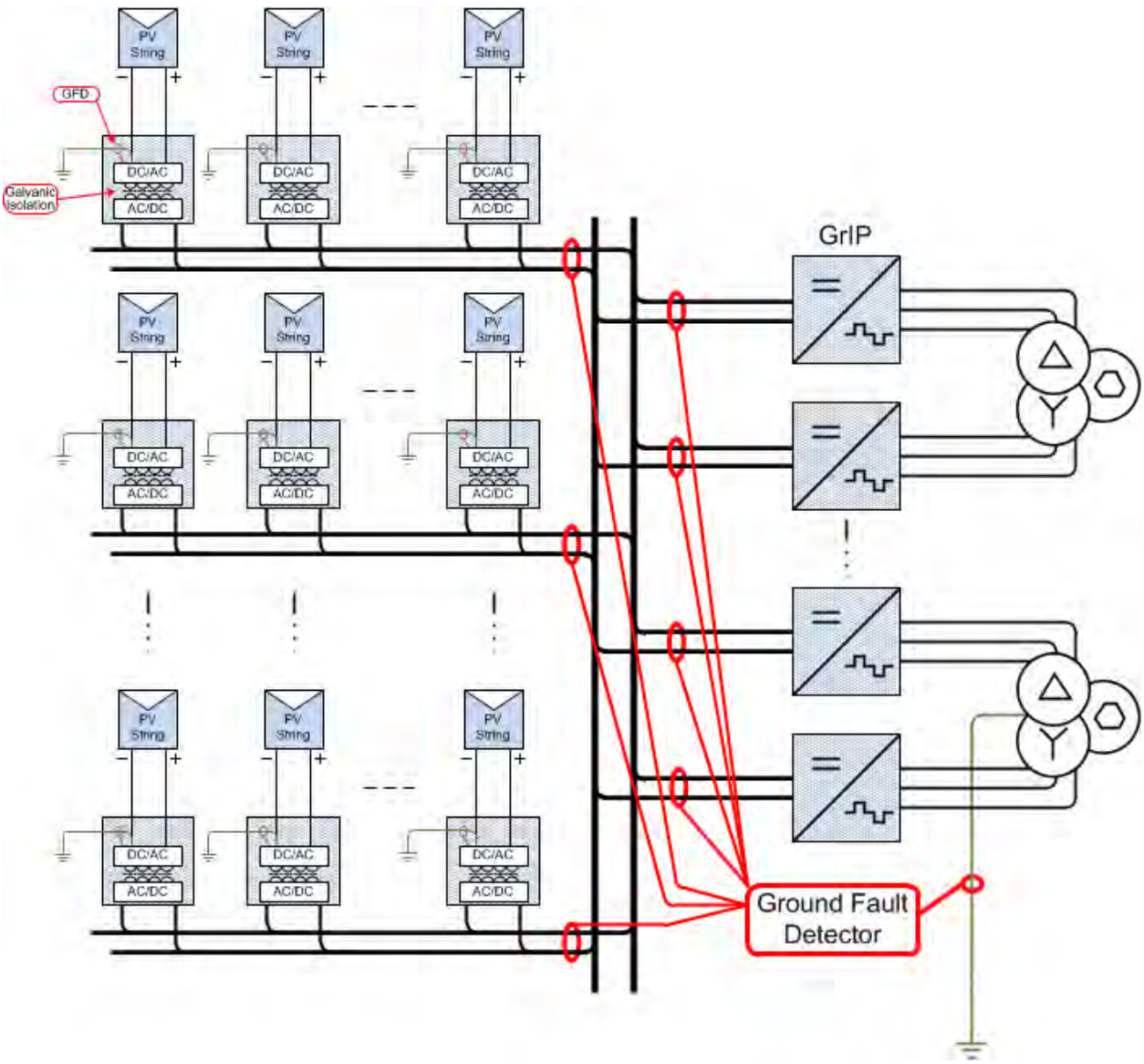



**Figure 49. Ground Fault Detection Scheme**

In Q1 2014 the process of selecting hardware for the centralized bus continued, including the selection of DC contactors for the connection of the 500kW PV arrays at high voltage, DC fusing, ground fault protection, and surge protection. This culminated in the completion of a preliminary design which was displayed at the 2014 Solar Power International Expo, shown in figures 46-48.

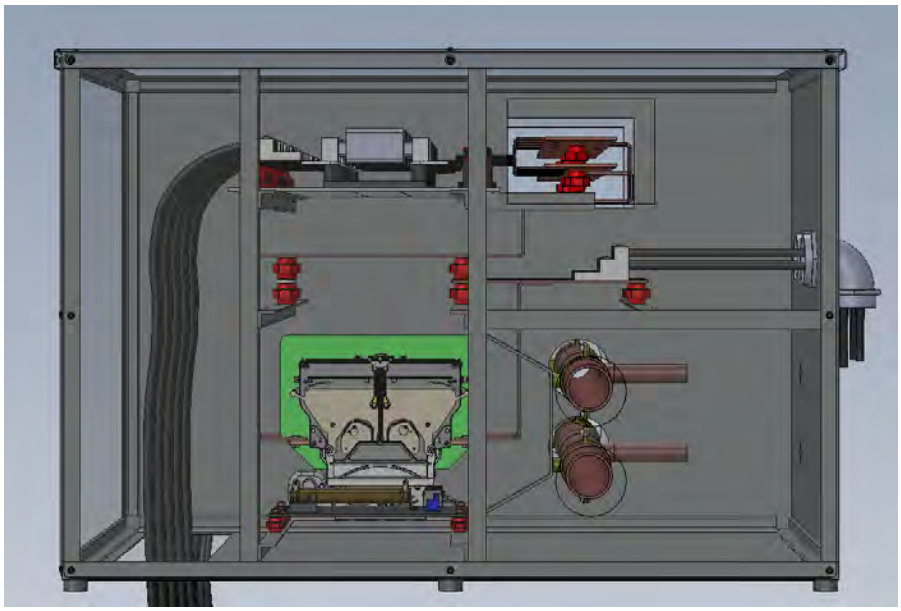


**Figure 50. Docking Station DC Side View**

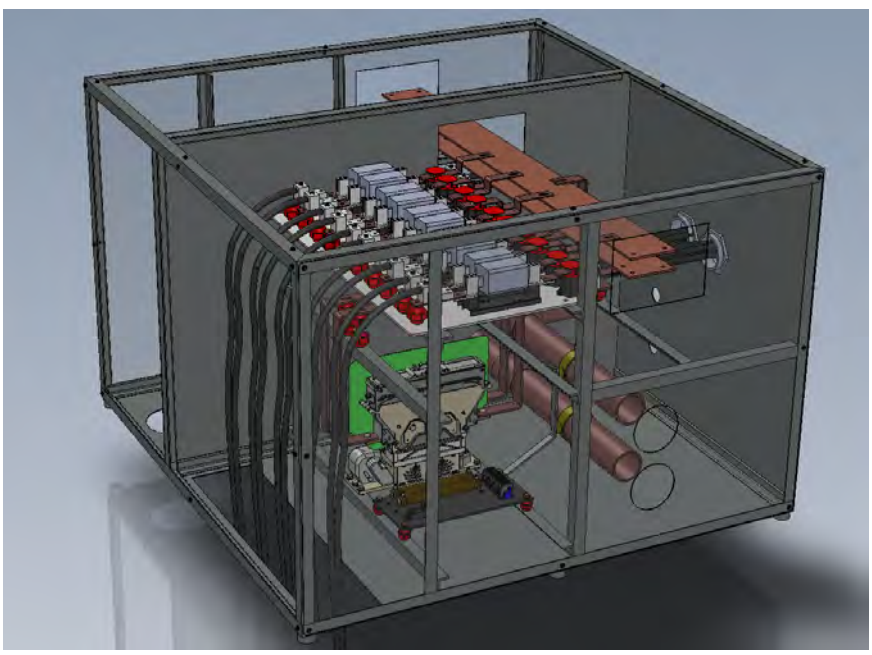


**Figure 51. Docking Station DC Input**

The preliminary docking station design contained the main DC contactor for its respective GrIP, as well as 5-10 landings for incoming DC trunks. These included fusing and contactors for servicing and disconnection.

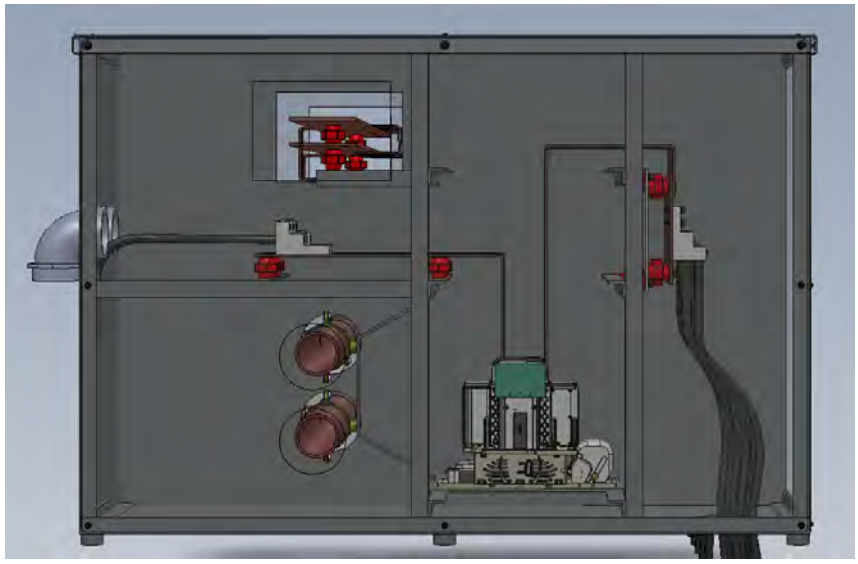


**Figure 52. Docking Station AC Side View**

In addition to the DC side, the AC output of the GrIP was tied to the transformer via the dock, which contains an AC contactor and optional AC fusing.

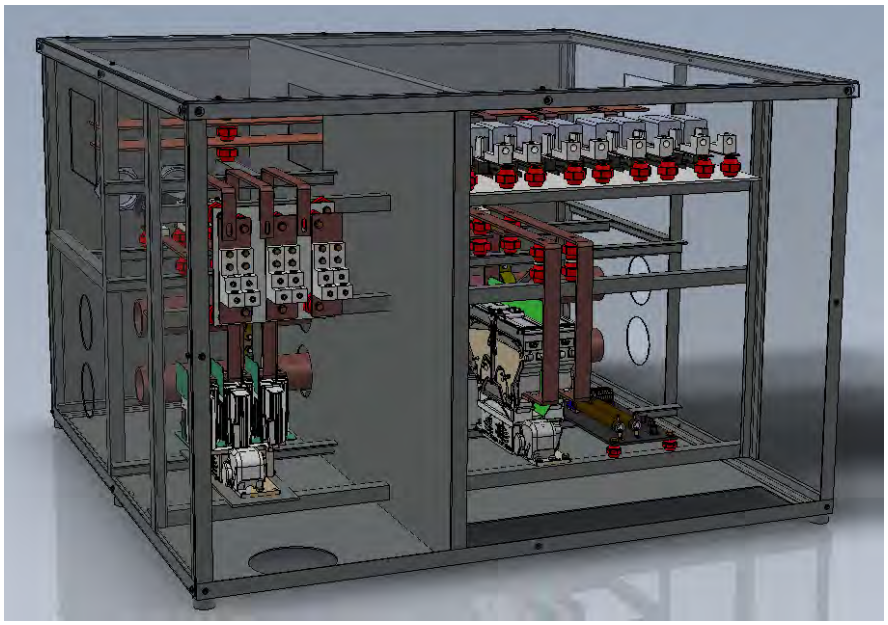


Figure 53. Docking Station AC (left) and DC (right)

In Q1 of 2015 the preliminary Docking Station was redesigned to a final production version, shown in Figure 53.

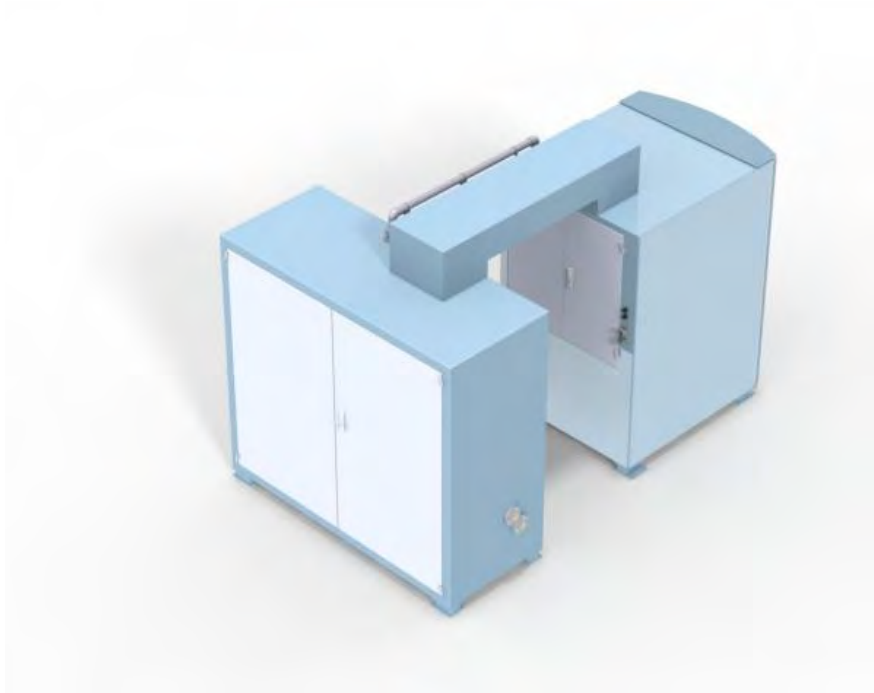


Figure 54. Production-Ready Docking Station and GrIP

Major changes included routing the AC output from the GrIP and the GrIP DC input overhead. The electrical connections were designed with bus bar inside a single frame (figure 51) rather than passing multiple wires through multiple conduits, as was intended for prototype Docking Station. This allows for a service person to easily access the back of the GrIPs without having to avoid an excess of conduit.

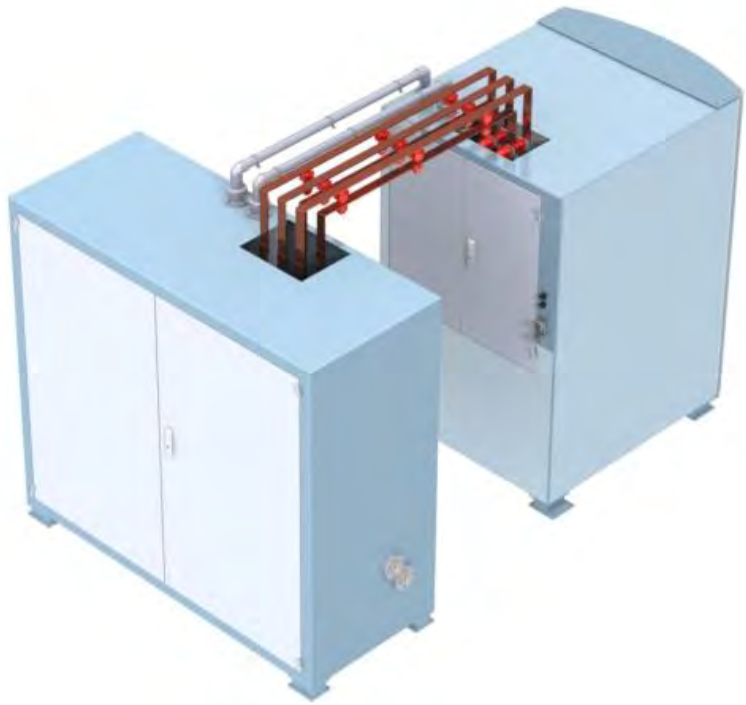


**Figure 55. Electrical Connection between Dock and GrIP is made via bus bar.**

Additionally the internal layout of the dock was modified so as to reduce the depth of the enclosure and increase the height, allowing for greater serviceability and user-friendliness. Overall, the final production version of the Docking Station is designed to be serviceable, robust, easy-to-assemble, and easily-configurable in parallel, as in the 10MW system shown in Figure 56.

**Figure 56. The docking station is assembled in modules to form a system. 10MW system shown.**

#### *5.3.1.4. SubTask 10.4 Certify Equipment*

In Q1 of 2014, efforts on incorporating changes to the GrIPs to ensure compliance with certification requirement and regulations continued. This had led to changes in the design of the next iteration of the GrIP control board, and would continue to play a role in its development. Active participation by Alencon in the IEEE 1547.1a, P1547a workgroups also helped to ensure that future requirements would not be impediments to Alencon.

In Q2 of 2014, the creation of the documentation required for UL engagement was in full swing. The fault analysis of the GrIP is a document that, along with the test plan, greatly helped to facilitate a smooth compliance process. A robust anti-islanding algorithm had also been developed for the inverter system that would not be impacted by the implementation of future smart inverter functions.

In Q3 of 2014, UL had been engaged and the creation of the detailed test plan was under way. Internal testing was to commence in October, while the final features were being implemented in the software.

### 5.3.2. Task 11.0: SPOT Testing and Certification

The SPOT testing and path to certification was broken down into five subtasks: Simulation and Testing, Communication Development, a Safety Analysis, construction of PPP SPOTs, and then SPOT certification.

#### *5.3.2.1. SubTask 11.1 SPOT Simulation & Testing*

The first PPP prototype was built in Q1 of 2014. This prototype consisted of consisted of four string level optimizers mounted on one standard off-the shelf heat sink extrusion as shown in Figure 57.

**Figure 57. Four-string SPOT with cover removed**

During this period, a SPOT test station (Figure 58) was built to test the complete SPOT.

**Figure 58. Production SPOT test station**

The SPOT test station was equipped with four 8 kW programmable PV String Simulators (total 32 kW) purchased from Magna Power and assembled into one rack shown in Figure 59.

Figure 59. 32kW PV String Simulators

In addition a 32 kW regulated resistor bank was built (Figure 60). The load bank is adjustable with 0.5 kW increments and can be controlled manually or automatically via a National Instrument DAC-USB6008 device.

Figure 60. Regulated 32 kilowatt load

The SPOT test station was also connected to a 24 kW test PV system comprised of four 6 kW PV strings. The system consists of a total of 80 PV modules, installed on the roof of Alencon's facilities. The installation of this system was delayed by a few months due to unexpectedly bad weather. Figure 61 shows the installation of the test PV system.

Figure 61. Installation of solar modules on Alencon roof

Figure 62. PV String Selection Box

Each one of the 6 kW strings is wired to the interconnect box in the SPOT test station. This interconnect box provides the ability to test a SPOT with a simulated source or with the actual PV modules on the roof. This box incorporates high voltage relays that are used to switch the SPOT's power source.

Figure 63. SPOT Test Lab in Use

Figure 64. 32kW Programmable Power Supply and Adaptive Load

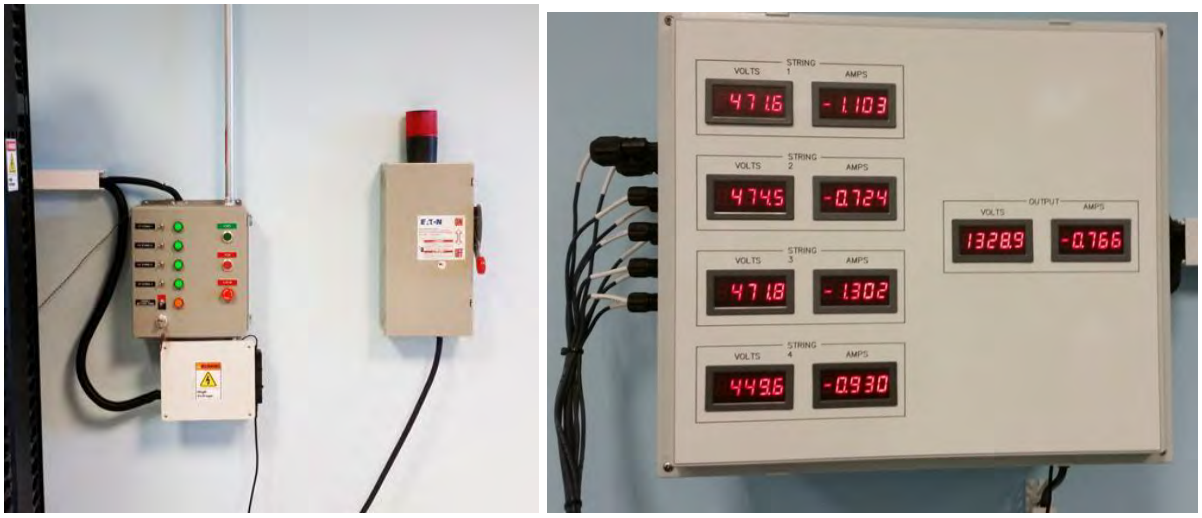



Figure 65. Interconnection Selection Box and Metering Meter Box

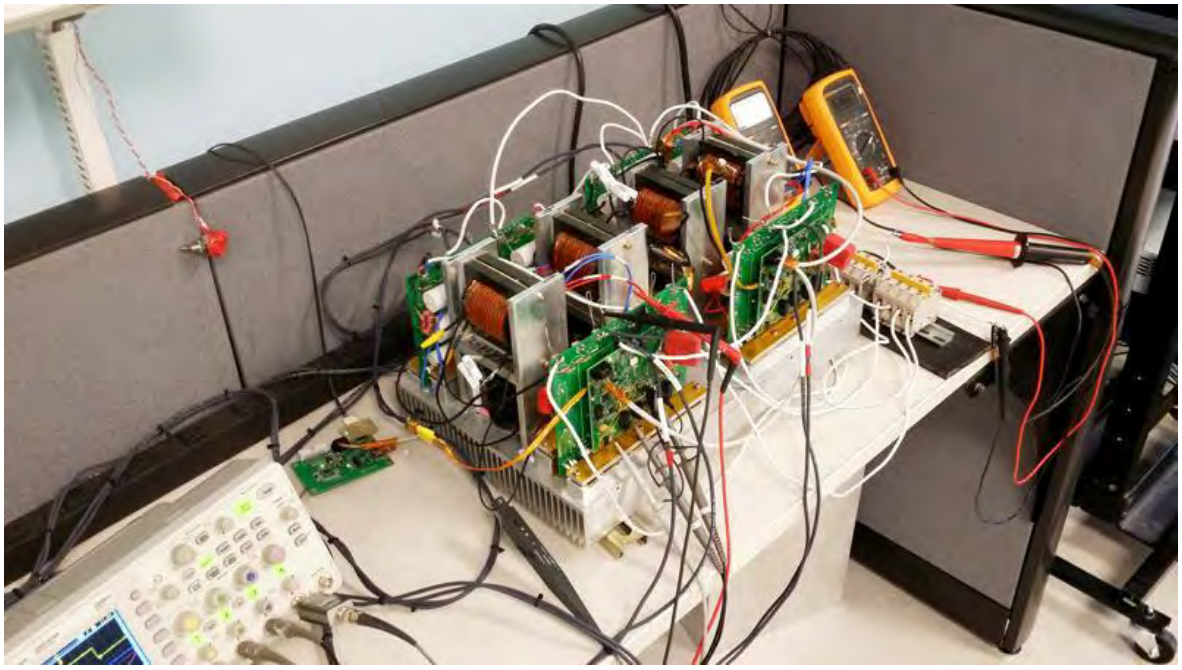


Figure 66. SPOT under Testing

The load bank control matches the load with the SPOT operation, thereby simulating a fixed DC bus by keeping the voltage stable (+/-1.5%).

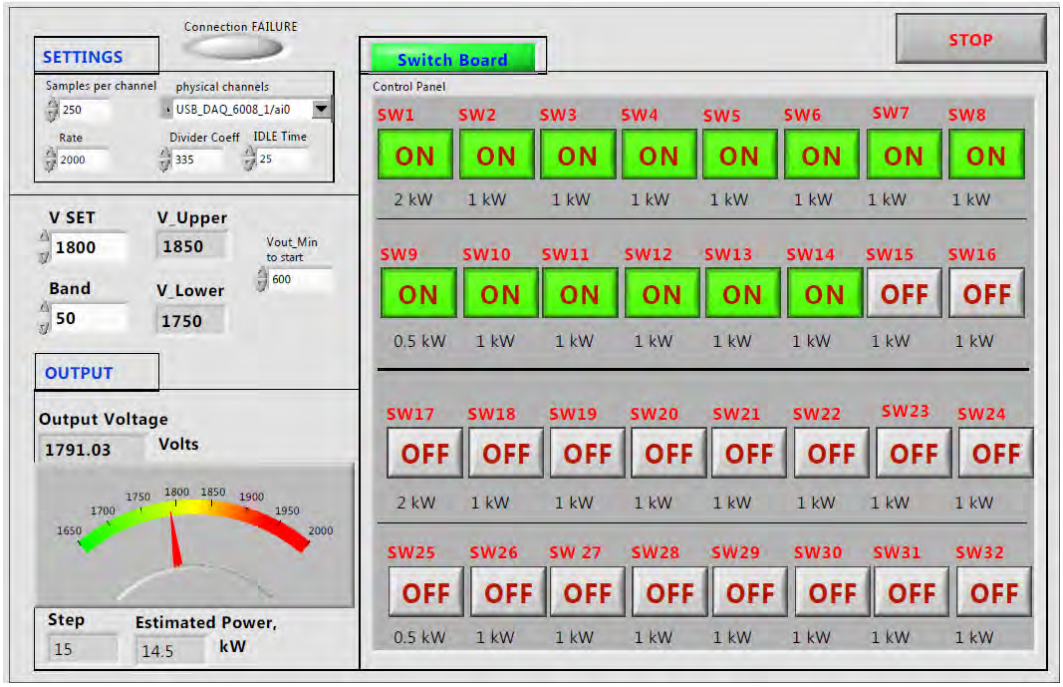



Figure 67. Load Control User Interface

In Q3 of 2014 the main focus was defining and improving the efficiency and reliability of the SPOT. To this effect, a great deal of performance testing and optimization was carried out.

## Efficiency testing

The units were tested using a handful of different magnetic designs. Based on these test results the performance and efficiency of the magnetics was able to be further improved.

This figure has been omitted for confidentiality reasons.

Figure 68. CEC Template for SPOT Testing

This figure has been omitted for confidentiality reasons.

Figure 69. CEC Template results for SPOT Testing

## Reliability Testing

In order to verify the reliability of the SPOT, the unit has been continuously run between July 21 2014 and the submission of this report. Each board in the SPOT is running its own MPPT algorithm to maximize the yield.

A few minor problems were discovered in the first two weeks, with initial testing showing a weakness in the handling of transients such as input/output voltage surges and current spikes.

Additional simulations and tests were performed to improve the operation of the unit, and the software was updated to include slow voltage ramping during startup and a current limiting mode to protect the semiconductors. Additionally, the frequency of the DC/DC operation was increased, and a few hardware (sensing) updates that were necessary were added to the board.

Starting August 12th (after the update) the unit was successfully run continuously without any issues. Figure 70 below shows log data for the month of September.

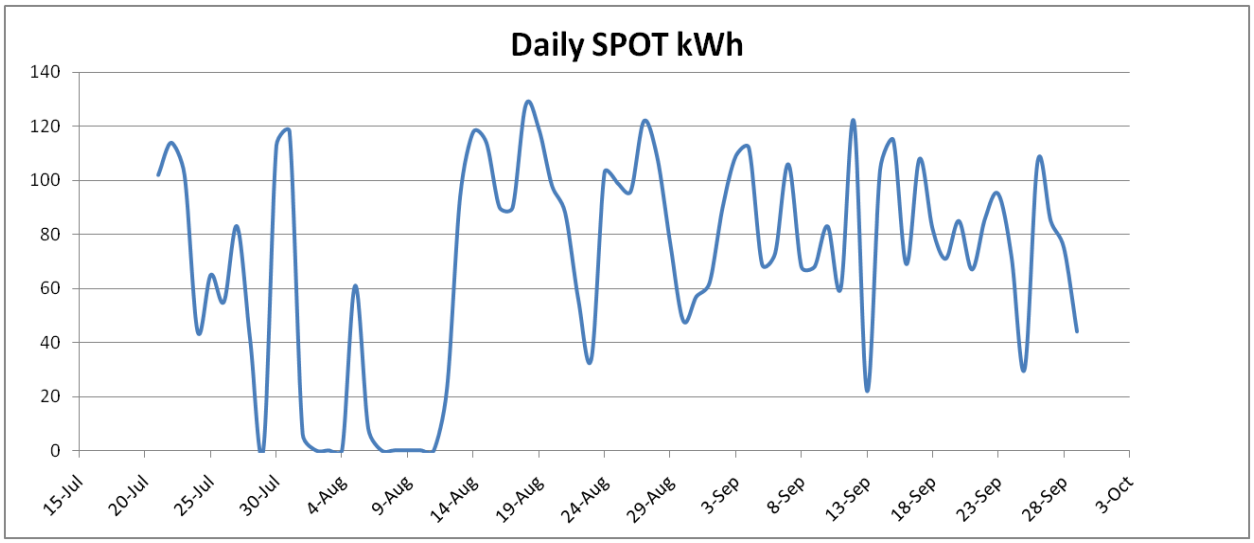



**Figure 70. Daily SPOT production**

As seen in Figure 71, the SPOT is capable of operating at a variety of voltages and currents while the output voltage stays fixed.

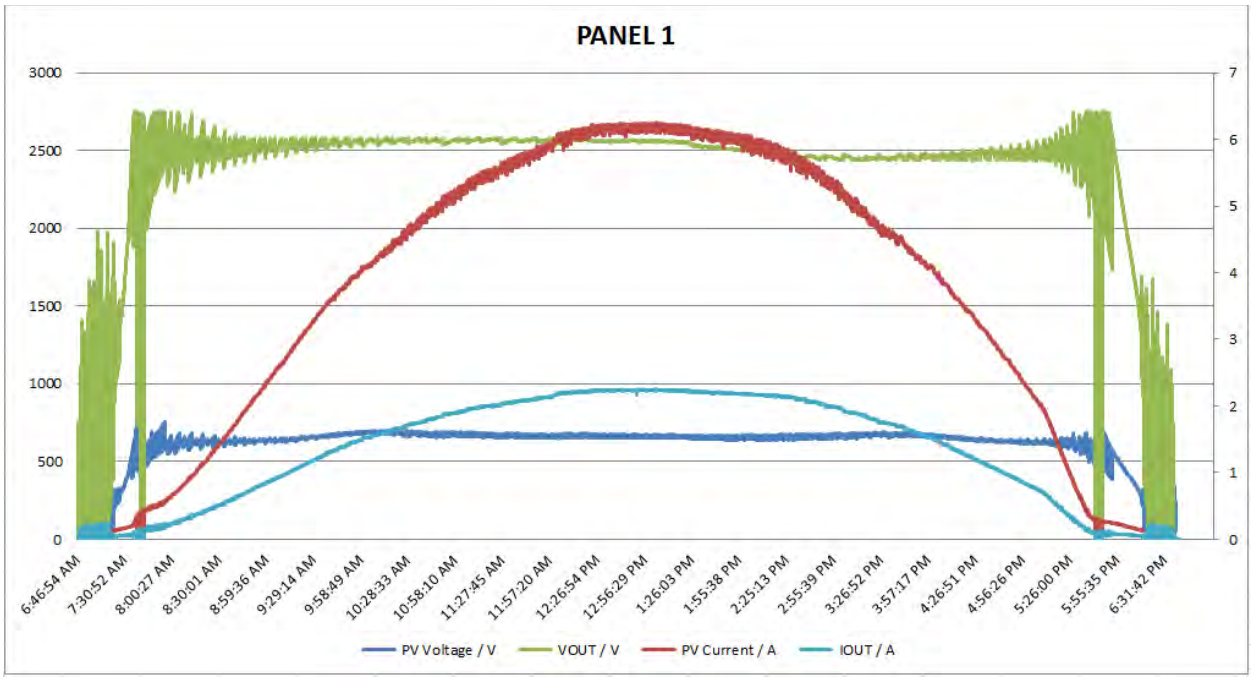



**Figure 71. SPOT Energy harvesting and stable voltage output.**

Figure 71 shows the daily log of the SPOT operation. The test setup consists of a PV string, SPOT and smart load. The load uses the array of resistors to adjust the power accordingly. The smallest step in the load is 500W, which causes large over and undershoots in the PV and output voltages, when there is <1kW of power available from the PV (see voltage ripples in the early hours of the day, and late hours of the evening). This behavior is caused by the setup and cannot happen in the real system, where the power intake is precisely controlled by the GrIP inverter.

#### *5.3.2.2. SubTask 11.2 Communication System Hardware and Software*

The high level specifications for the SPOT communications were finalized in Q1 of 2014. Each SPOT was designed to carry a transceiver on board, and communicate with one or more aggregators which in turn communicate with the central monitor. Specifications for the communications interface were written and are ready to be used for implementation. Figures 67 and figure 68 provides a block diagram of the components involved in the communications on the SPOT and aggregator, respectively.

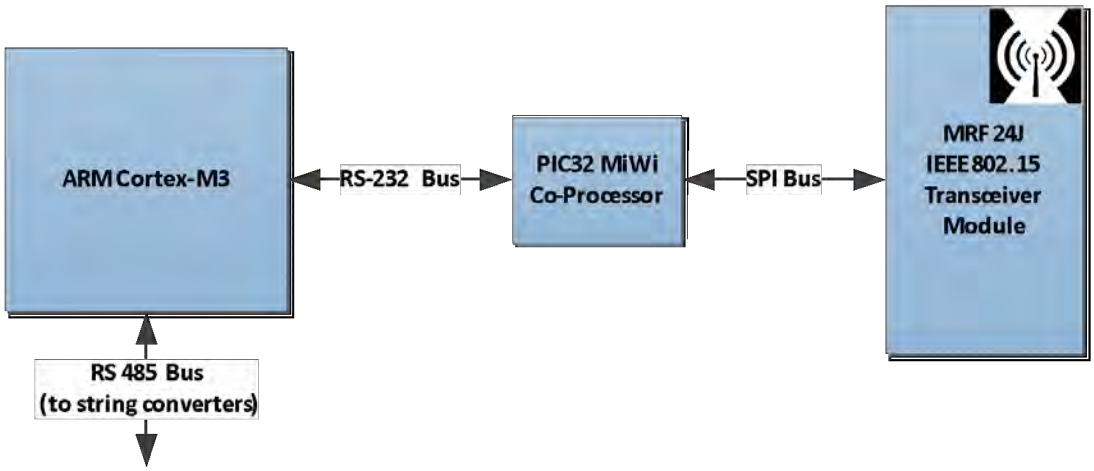



Figure 72. Block diagram of SPOT wireless communication board

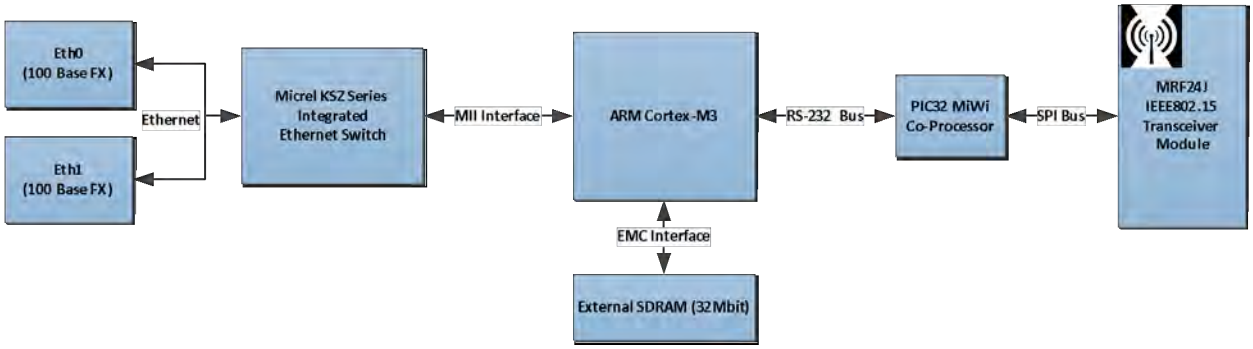



Figure 73. SPOT Aggregator Block Diagram

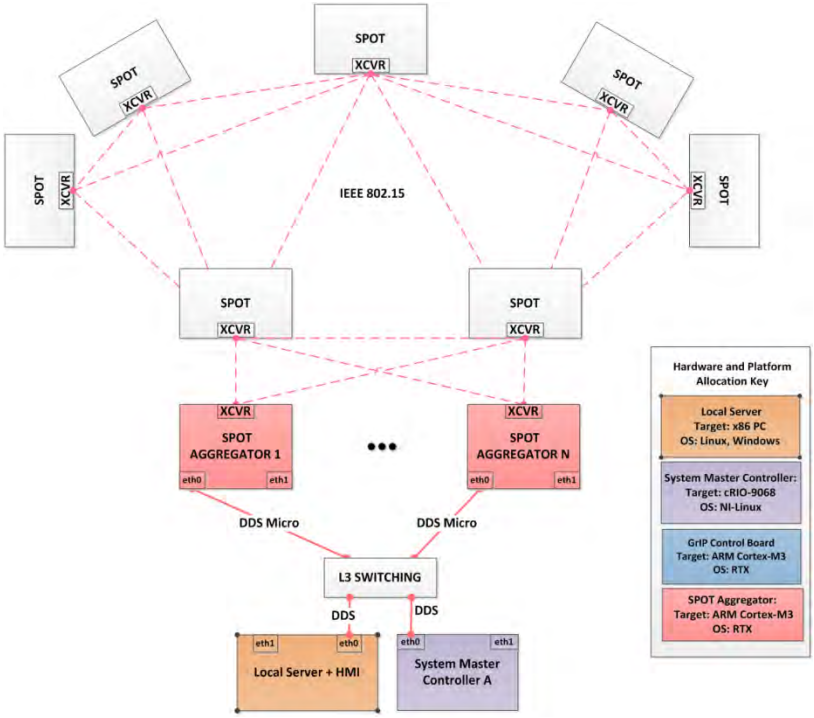



**Figure 74. Harvesting System Network Topology**

Figure 74 shows the overall topology of the wireless mesh network, aggregators, network equipment, local server/monitor and SMC.

By Q3 2014, the SPOT Communication PCB board was updated to revision 1.2, which included a communications processor update (16-32bit), added parameter storage memory, improved RS485 communication, improved power distribution, and an added a temperature sensor which includes a unique 48bit ID number which will be also used for as the unique identifier of each SPOT. Figure 75 and Figure 76 below show the schematic and PCB layout of the new board.

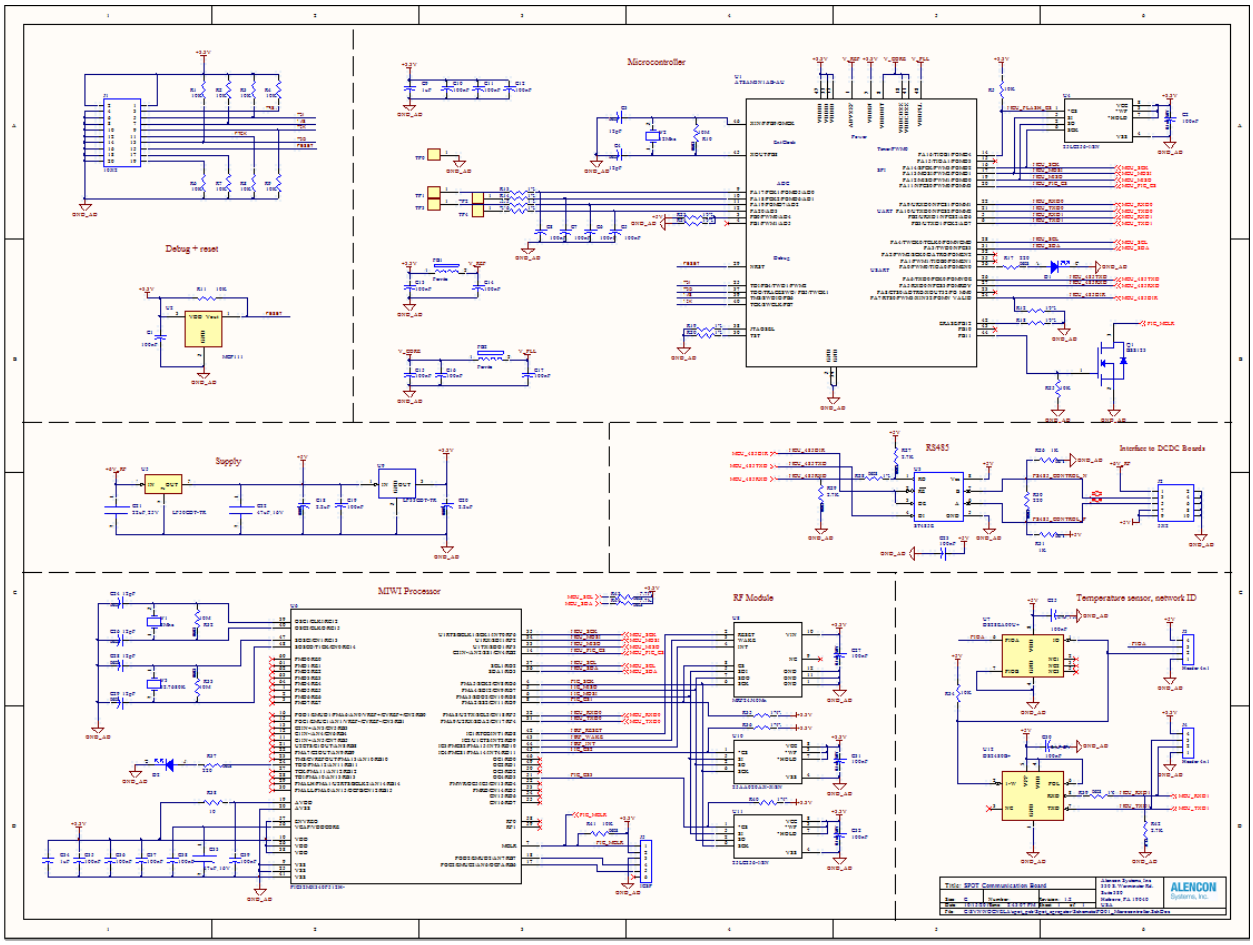



Figure 75. SPOT Communication Schematic

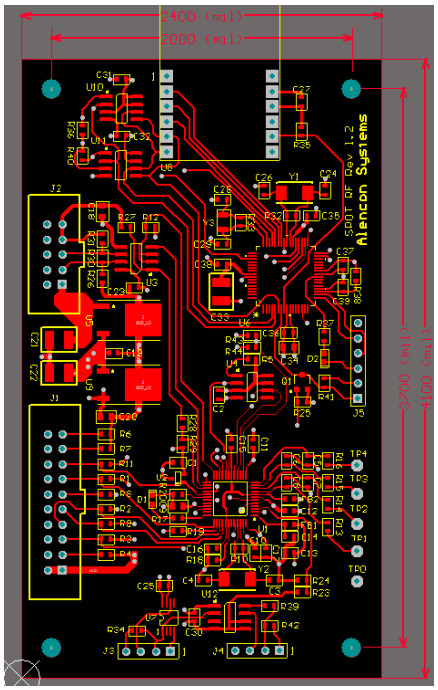



Figure 76. SPOT Communication PCB

### *5.3.2.3. SubTask 11.3 Produce SPOT Safety Analysis*

SPOTs were constructed with a number of safety and self-protection features built in, all of which were implemented and tested. Incoming string connections were made with off the shelf PV string connectors, making for a safe and familiar installation in the field. Galvanic isolation between the input and output meant that when the SPOT was not operating, it was physically disconnected from the source of power. A dedicated, insulated box for the high voltage connection to the branch bus provided a quick and safe installation of the larger output conductors. Though this design was not to last, it still represents a viable option for various circumstances.

In the SPOT, each PV String is galvanically isolated from others on the input of a SPOT, the output of these isolated voltage boosters only thereafter form a common output. This eliminated the possibility of shorting of one PV string to another, meaning that input fuses were not required (or useful).

On the connection to the common DC bus, each SPOT produces +/- 1,250 V. With the connection of multiple SPOTs in parallel to the DC bus, fusing on the output of each SPOT is provided to ensure any failure will not result in hazardous conditions.

One of the many benefits in the system is the distributed nature of the DC/DC converters. With this, ground currents are continuously monitored throughout the system, and give each SPOT the capability to disconnect if it exceeds a certain threshold, enhancing overall system safety and integrity significantly.

Finally, overvoltage protection (OVP) circuits automatically limit the output current of a SPOT if the common DC bus voltage exceeds a set limit. If output voltage is not reduced, the OVP circuit will crowbar the output terminals, either draining the bus or opening the fuses.

In Q2 of 2014 SPOT testing of overcurrent and overvoltage conditions were completed. The SPOT protection circuits handled them successfully.

The SPOT unit was also tested beyond its rated operating range starting in Q3, and the DC/DC converter circuitry was stress tested up to 1,000V input voltage and 10A input current. To enable these extreme test conditions, the magnetic parameters had to be changed while the PCB remained the same. The output voltage was tested up to 2,900V (rated 2,500V) and the output current of the single DC/DC board was tested to 4A (rated 2.5A). The circuits handled the stress without any noticeable problem, giving a comfortable reserve for future performance improvements.

#### *5.3.2.4. SubTask 11.4 Build PPP SPOTs*

The BOM and manufacturing drawings for the PPP spot was sent out to suppliers and manufacturers in Q1 of 2014. Simultaneously, subcontractors were asked for quotes to allow for the production of subassemblies, with the final assembly of the SPOT being done in-house. The selection process completed at the end of Q3 2014, with the plan to complete the manufacture and assembly of the first 25 SPOTs in Q4 of 2014. The first pre-production SPOT was assembled without major issues, except that it was noted that the assembly process was extremely slow and difficult due to the nature of the mechanical design. A revision to the design to incorporate optimizations for the assembly of the SPOT, as well as input from the contract manufacturer continued into Q1 2015.

#### *5.3.2.5. SubTask 11.5 SPOT Certification*

Initial contact with UL engineers was made in Q1 of 2014, with the design drawings and BOM to be sent to UL in June. With the information provided, an initial review was completed by UL, after which they requested additional information on the PCBs, enclosure and schematic designs, as well as various materials used in an analysis. This information was provided, and led the first iteration of discussions between Alencon and UL with regards to the exchange. A preliminary design review began in Q4 2014, with some changes to the SPOT enclosure proving to be a hold up for moving forward. Certification has continued now that design iterations and updates have completed. Additional updates were made to enhance SPOT safety capabilities, which may be included as product options.

### 5.3.3. Task 12.0: System Integration

The integration of the various systems in the Alencon topology is one of the final tasks in the project. This includes the complete analysis via modeling and simulation of the system as a whole, as well as completing the communications interfaces, and SCADA capabilities. This task was broken down into three subtasks: The simulation and analysis of controls, the completion of communications for all of the devices on the network, the completion of the SMC, and the completion of the SCADA system.

#### *5.3.3.1. SubTask 12.1 Simulate and Analyze System Controls*

Q1 2014 focused on fine tuning the controls for the inverter system, as well as testing to ensure abnormal conditions would not be able to cause operational states which may compromise its safety

and stability. Simulations on the inverter system were confined to the detailed specification of component updates, as well as the finalization of the load requirements for UL testing. Various simulations for system behavior under certification testing were completed, including the operation of the RLC load and the various abnormal tests required for UL certification.

**Figure 77. Capacitive load simulator.**

Additionally, in order to simulate the operation of a large field of SPOTs in the lab, a power source simulator was created, see Figure 78. It is a controllable voltage-fed current source, which enables the ability to fix the amount of power that is supplied to the inverters. This is necessary due to the fixed duty cycle control scheme implemented in the inverter system.

**Figure 78. Power-source simulator.**

### *5.3.3.2. SubTask 12.2 Complete Communication for SPOTs, GrIPs and the SCADA system*

See Tasks 10.2 and 11.2 for descriptions of work completed with respect to GrIPs and SPOTs respectively. For the SCADA and SPOT aggregator communications, a DDS databus was also utilized. The same data model and generated libraries will be used for integrating these applications, cutting the development time down significantly. Several services were under scrutiny by Q2 to provide the local and remote data logging capabilities that will come with the Alencon system. The DataStax's Cassandra database services were selected as the primary technology of interest for high-speed distributed logging components. DataStax provides and supports a very robust database and analytics solution that lends itself well for time series data. The final network topology can be found in Figure 79 below.

The updated DDS implementation was completed and performance issues were resolved by Q2 of 2014, allowing for sub-cycle command-response times. A custom Data Model has been completed and is being utilized by the latest revisions of code for communication purposes. QoS settings have also been customized to fit Alencon's needs.

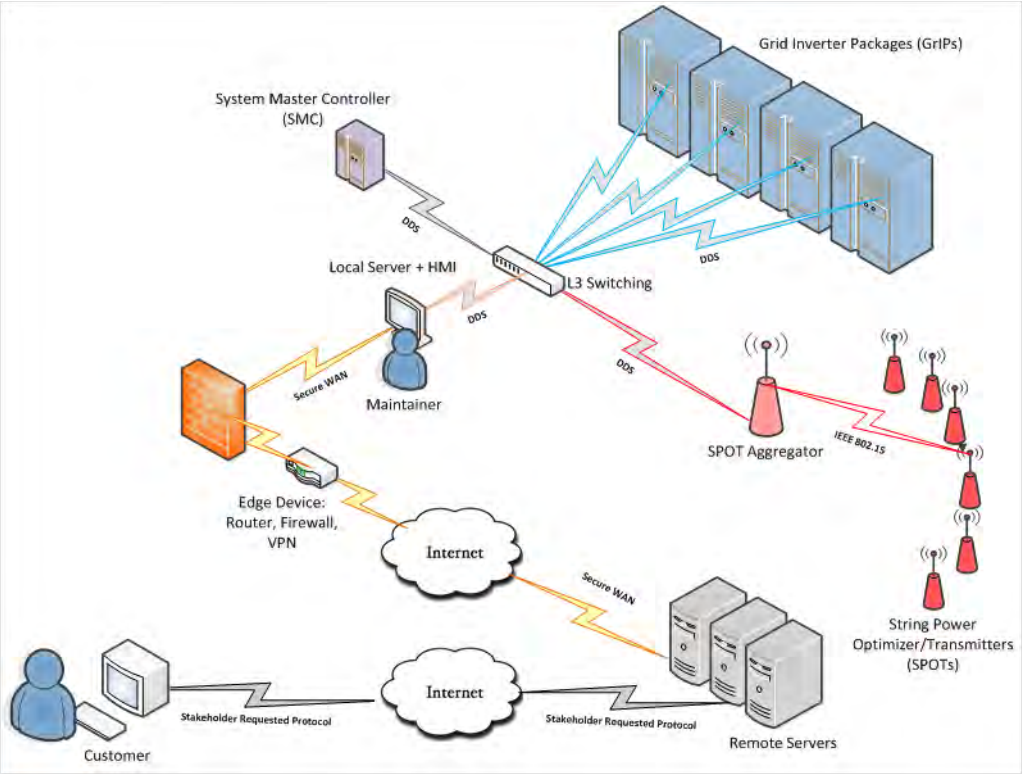



**Figure 79. Local and Remote Communications**

Work in earnest on VIEWS began in Q2 2014, to display in a meaningful and intuitive way to visualize all of the data that is collected from the GrIPs in the lab.

In Q2, data from the DDS bus was read by VIEWS through the use of a set of JSON files that also helped to decouple the systems. This meant that real data from the GrIP units was being used in VIEWS to graphically represent the operations of the system.

In Q4 of 2014, a prototype for the secure WAN communications link between VIEWS and the local system monitor was implemented. This prototype is based on a secure, open source, distributed, in-memory key-value store known as Redis. Redis is employed heavily in distributed web-based technologies developed by companies such as Instagram, Twitter, Snapchat, Flickr, GitHub, and others. Implementation of the SPOT Aggregator communications and initial platform testing were also under way during this time.

#### *5.3.3.3. SubTask 12.3 Complete, Test, and Integrate System Master Controller, Finalize the SMC control algorithms and interface to the GrIPs, SPOTs and peripherals. Test SMC controls.*

In Q1 of 2014, the cRIO based SMC replaced the GrIP Monitor application for testing for the first time in the power lab. The software was continuously updated and tested as the base feature set for system control was developed.

In Q2 of 2014, application development was well along the way on the SMC. Performance testing had validated the cRIO's selection for this crucial role in the Alencon system, and features were continuously updated as testing continued.

**Figure 80. SMC hardware setup in the lab**

In Q3 of 2014, the remote dissemination of calibration and configuration information for GrIP control boards had been completed. This allowed for the generic use of control boards and units that could be updated with the configuration details needed to operate in a system. The most prominent example of this application was the phase shift of the individual GrIPs; the location on the phase shifting transformer determines the phase shift of the unit, which must either be sensed on each GrIP control board. If this was not done by the SMC, each GrIP would have to be programmed separately to ensure their proper shift.

#### *5.3.3.4. SubTask 12.4 Complete the SCADA System*

In this subtask, Alencon finalized the data logging software/hardware that will enable comprehensive monitoring of the beta PV system. This may either be an in-house or off-the-shelf solution (the customer will be able to choose). The SCADA system is capable of communicating with remote utility systems using standard protocols such as DNP3.

A virtual copy of the Alencon lab was created to help provide visual indications of the operation of the units under test. The search for intuitive and meaningful data visualization techniques continued throughout Q3, with mockups to generate more ideas showing useful information.

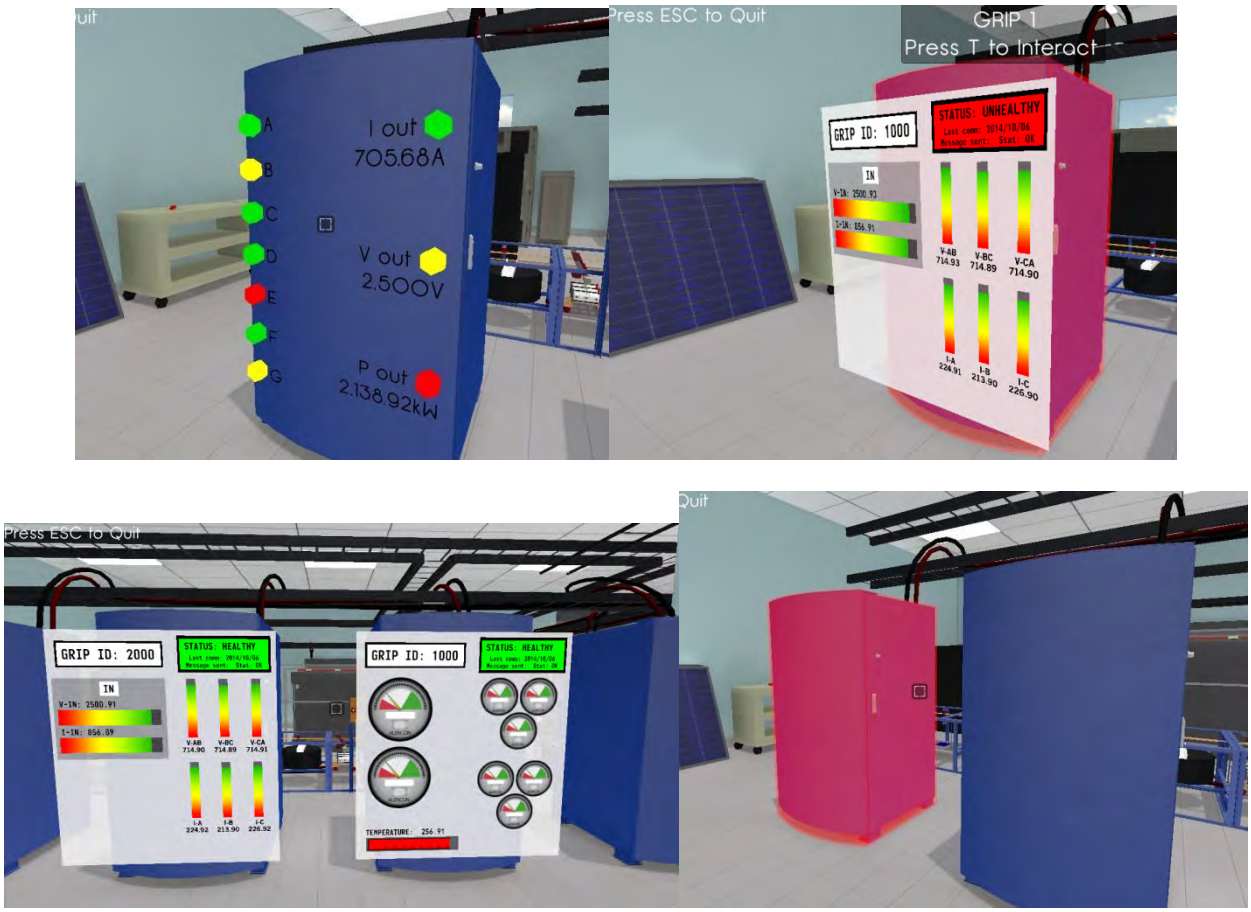



Figure 81. Experimenting with data visualization in VIEWs.

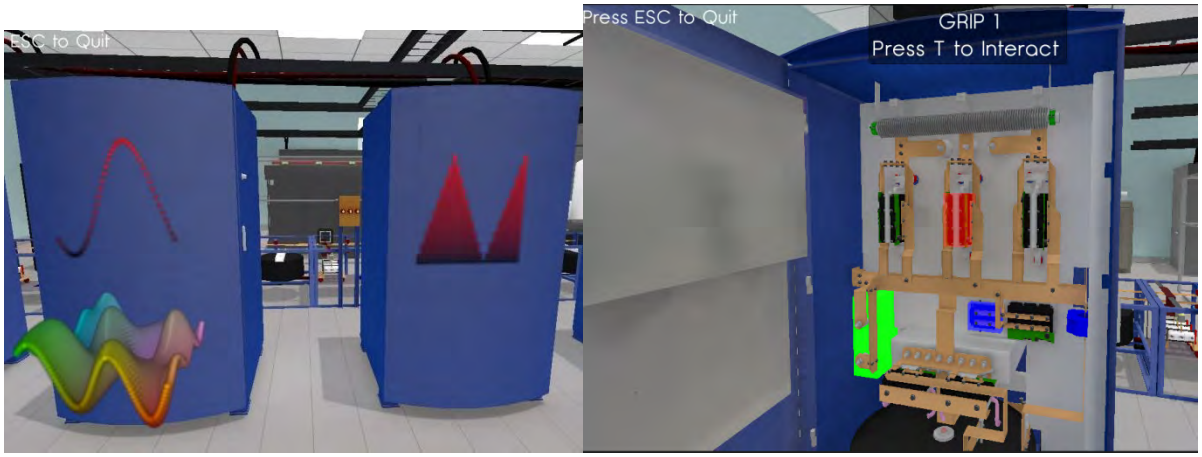



Figure 82. Data visualization techniques under investigation

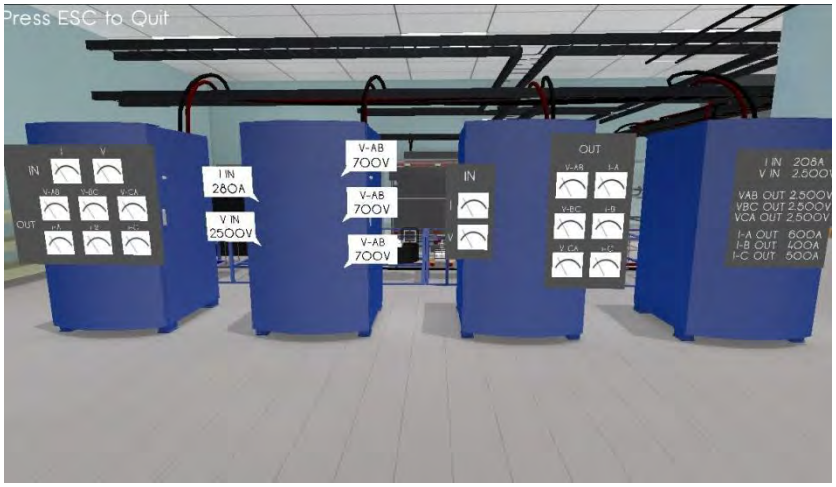



**Figure 83. Inverter dashboard popup example**

By the end of Phase 3, VIEWS had already been extremely useful in the testing of the inverter system in the lab, and more features were added. Users could select which set of historical data would be graphed, engineering dialogs could give information on the connectivity, configuration and calibration of sensors, and in depth data on the status of the unit. Temperatures on the heat sinks could be numerically and graphically displayed to indicate performance and highlight issues with flow.

**Figure 84. GrIP Overview visualization.**

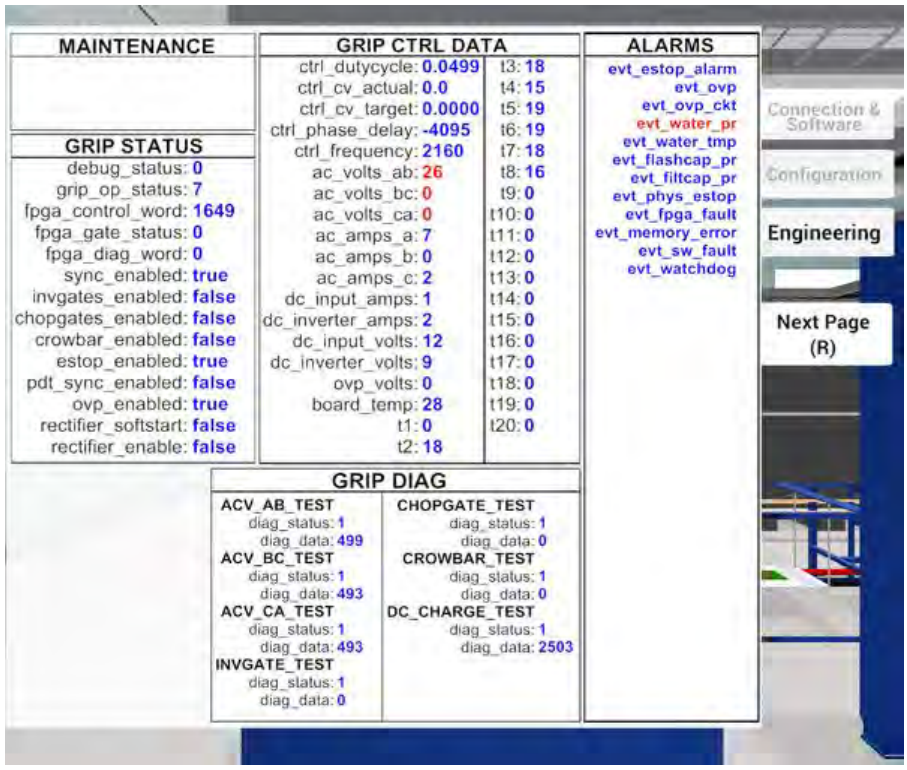



Figure 85. GrIP Detailed View

Figure 86. GrIP temperature visualization.

A 3D model of the beta system to be installed on the roof was also completed, with SPOT data to be populated over the wireless connection (figure 87).

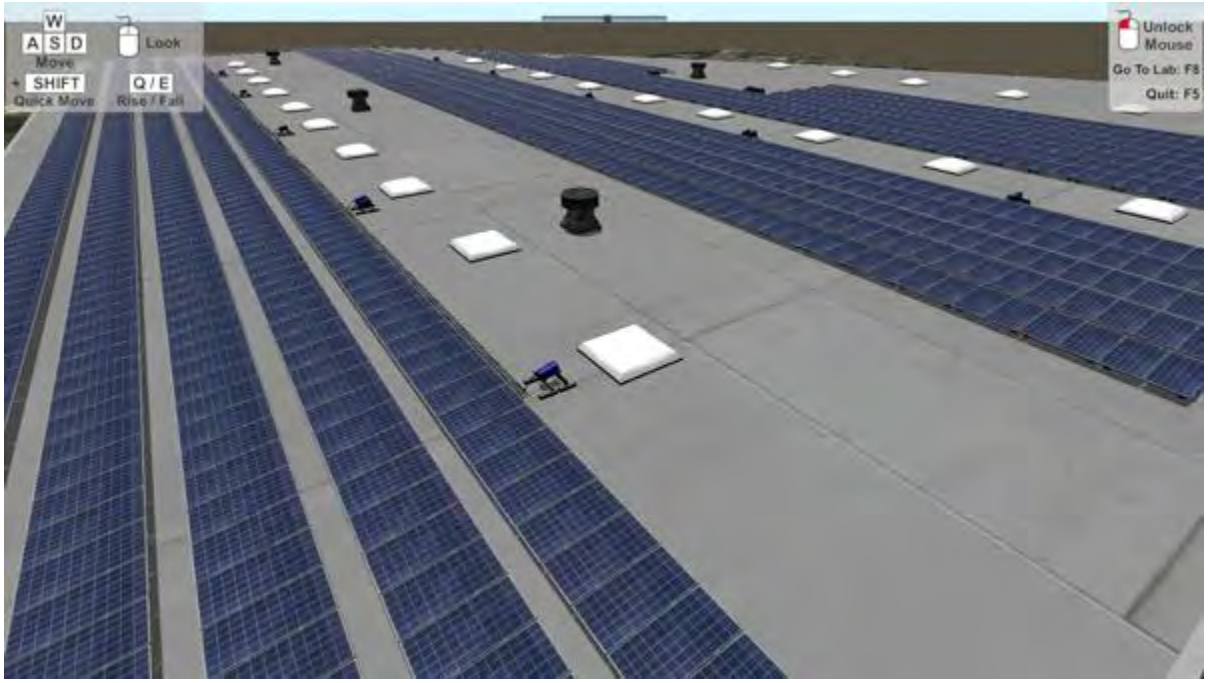



Figure 87. VIEWS model of Alencon Beta Site

### 5.3.4. Task 13.0: Beta PV System Engineering, Certification, and Field Validation Testing

Preliminary layouts for the beta site were completed at the end of 2014 which laid the groundwork for continuing its development. PPA negotiations finally came to a close in December of 2014, and an EPC agreement was signed between Alencon and a third party to provide funding for the beta site was signed at the end of December.

Timing for the construction is now largely dependent on the completion of the first 25 SPOT devices from the contract manufacturer. Once these are received, construction of the beta site can begin culminating in the supply of 2,500V DC in the lab for use in integration testing with the inverter system. Upon certification of the GrIPs and the inverter system, an interconnection with the utility can be made and the beta site completed. The beta site was broken down into two phases: the installation of the PV system along with the SPOTs on the roof, wired back to the lab, and the full completion of the beta site with interconnection of an inverter system to the utility. A contractor was selected to complete the first phase, which will begin once the SPOTs are manufactured.

### 5.3.5. Task 14.0: Prepare GrIP and SPOT designs for Production

Both the GrIP and SPOT designs have gone through numerous iterations, ending finally in what are believed to be production-ready products.

#### *5.3.5.1.SubTask 14.1 Streamline GrIP design for Fabrication*

Final modifications to the design of the GrIP hardware were made in Q1 2014, which included easier access to the components in the rear of the unit for production, as well as greater allotments for the

spacing of incoming and outgoing conductors. The preliminary interface to the docking station was designed at this time, consisting of flexible wire routed through flexible conduit, as shown in Figure 88.

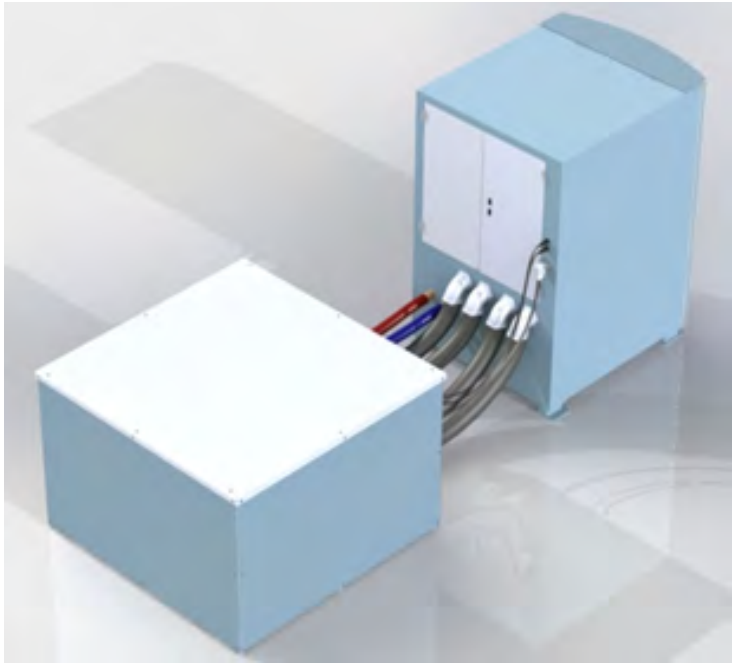


**Figure 88. Preliminary connection between Dock and GrIP.**

In Q2 and Q3 the GrIP design was updated to reduce costs, provide greater access to installation and maintenance personnel, comply with UL requirements on design, as well as reduce the potential for damage to the unit through internal component faults. Some of these changes also brought added benefits in terms of the efficiency of the unit. The removal of the superfluous input inductor reduced conduction losses, and the use of higher current IGBTs and Diodes in the inverter, afforded by a new chill block, reduced losses there as well. This had the effect of increasing the overall efficiency of the unit, relative to what was originally assumed.

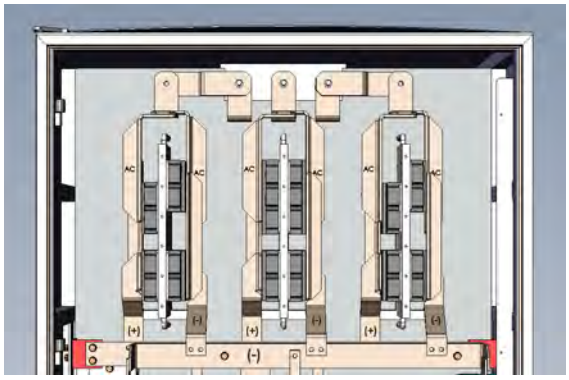


**Figure 89. Updated chill block design**

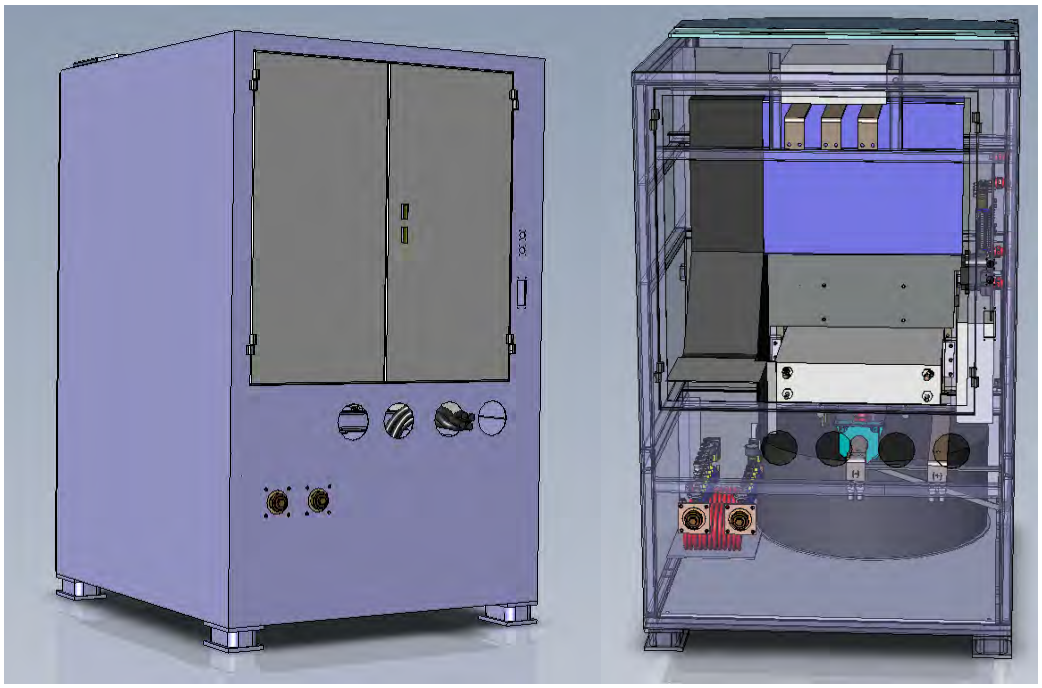


**Figure 90. Extended GrIP enclosure**

The GrIP cabinet extension allowed for greater access to the rear of the unit, and enabled the use of conduit connections to the docking station. Both AC and DC connections, as well as water connections, were to be handled in the rear of the unit and come from the centralized docking station.

A baffle covering areas with the potential for coolant leaks was also added, separating the electrical portion of the inverter from the leak.

In Q4 of 2014, the GrIP design was assessed and minor modifications were made to increase the quality of the device. The latching system was redesigned, and minor structural modifications were made to the enclosure. In Q1 of 2015, the interconnection between the dock and the GrIP was redesigned to accommodate an overhead electrical connection. This resulted in a minor redesign of the GrIP enclosure. The redesign eliminated the provision for conduit hubs in the back of the device, and an opening was made in the top rear of the enclosure so that the AC and DC connections could be made via bus bar. Additionally, the water-cooling manifolds were moved from the rear of the device to the top of the device, so that the input and drain piping could come from overhead instead of in the rear of the device. This had the effect of increasing device serviceability via the back panels of the GrIP. The production version of the GrIP is shown in figure 86 (bus bar covering not shown).

**Figure 91. Overhead bus bar connection between GrIP and Dock.**

As of Q1 of 2015, the preliminary review of mechanical design was completed by UL with no major design modifications indicated. The review of the GrIP design by UL will continue into Q2.

| | PPP GrIP | Production GrIP |
|---|---|---|
| Peak Efficiency | 99.3% | 99.5% |
| Cost Reduction | | 15% |
| Power Components | 17 | 19 |
| Weight | 4200lb | ~3700lb |
| Dock Connections | Cable & Conduit | Bridge Buses |

### *5.3.5.2. SubTask 14.2 Modify SPOT Design for Mass Production*

SPOT packaging underwent an extensive design and review as of Q1 2014. First variant shown in Figure 92 upon evaluation from DFM analysis proved to be prohibitively expensive, primarily due to custom extrusion of the enclosure that incorporated a heat sink. However many features, such as lay-in terminals for interconnection cables, were deemed to be beneficial in reducing assembly time.

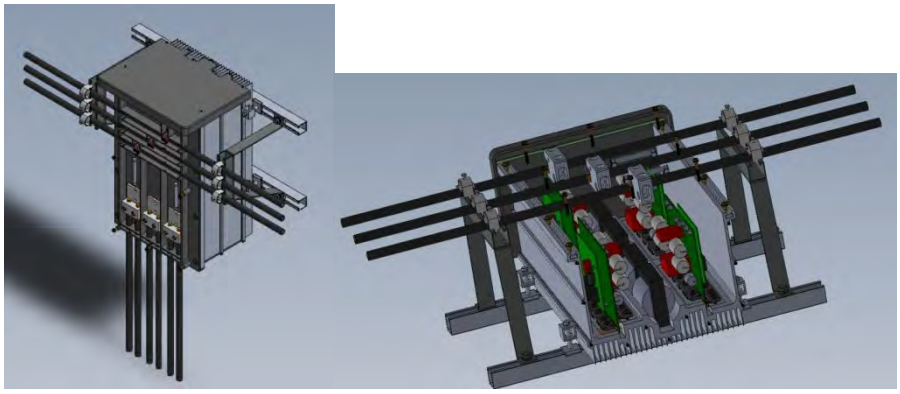


Figure 92. First iteration of SPOT quick interconnect.

Q1 2014 saw the second iteration of SPOT mechanical design come out much cleaner (Figure 93). It was also determined to be significantly less expensive in manufacturing.

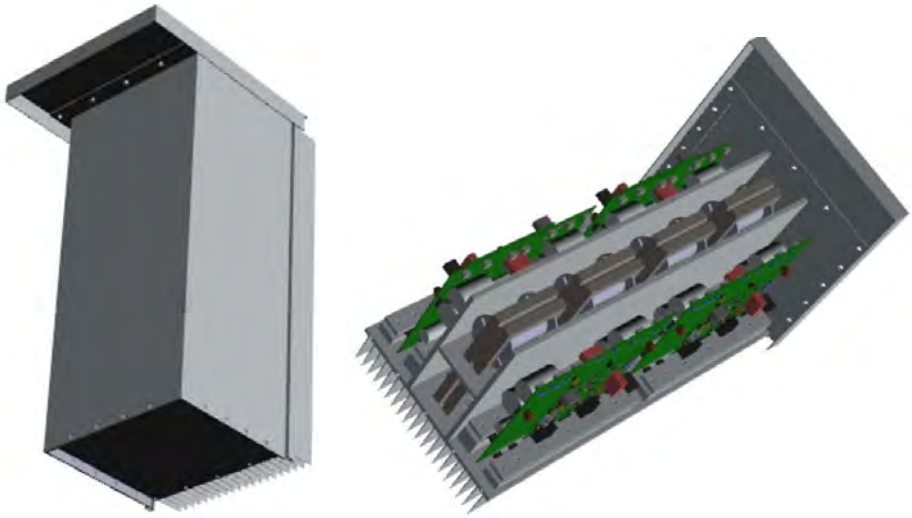


Figure 93. Second iteration SPOT. Cost reduction

Moving into Q2 2014, the modifications in the design of the SPOT revolved mostly around its interconnection to the DC bus system. Two versions were therefore created, one with pre-manufactured harnesses routed over molded junctions that are readily available from third party vendors, and a second with a proprietary interconnection box that allows for the use of off-the-shelf cabling.

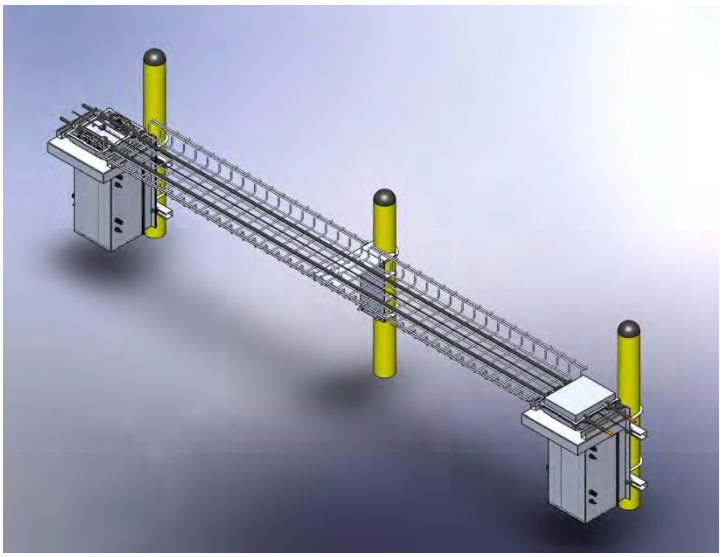


**Figure 94. SPOTs with wire tray and interconnection boxes.**

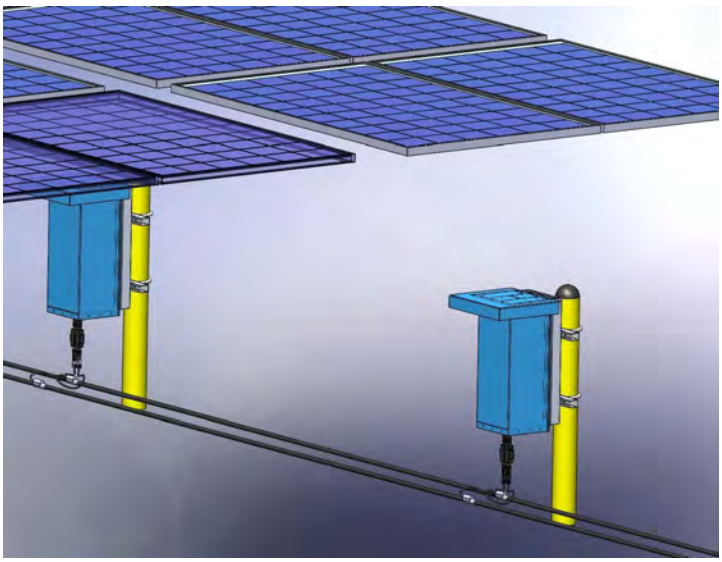


**Figure 95. SPOTs with pre-manufactured cabling and over-molded junctions.**

As of Q3 2014, the SPOT electrical design was locked in its current state to be utilized for the beta site. The PCB was updated to revision 1.3, which was designated to serve as the first production revision with the code name A-000183 (SPOT PCB Assembly). In this revision we merged the control and power circuits to one board, optimized the driver circuit, and added current sensing circuit and future options to detect arcing and ground faults.

Moving into Q4 2014, the mechanical design again went under extensive review and several major modifications were made: a new heatsink was designed to better dissipate heat and to serve as the

enclosure, and the internal layout was modified to maximize ease-of-assembly. The final production version SPOT is shown figure 96.

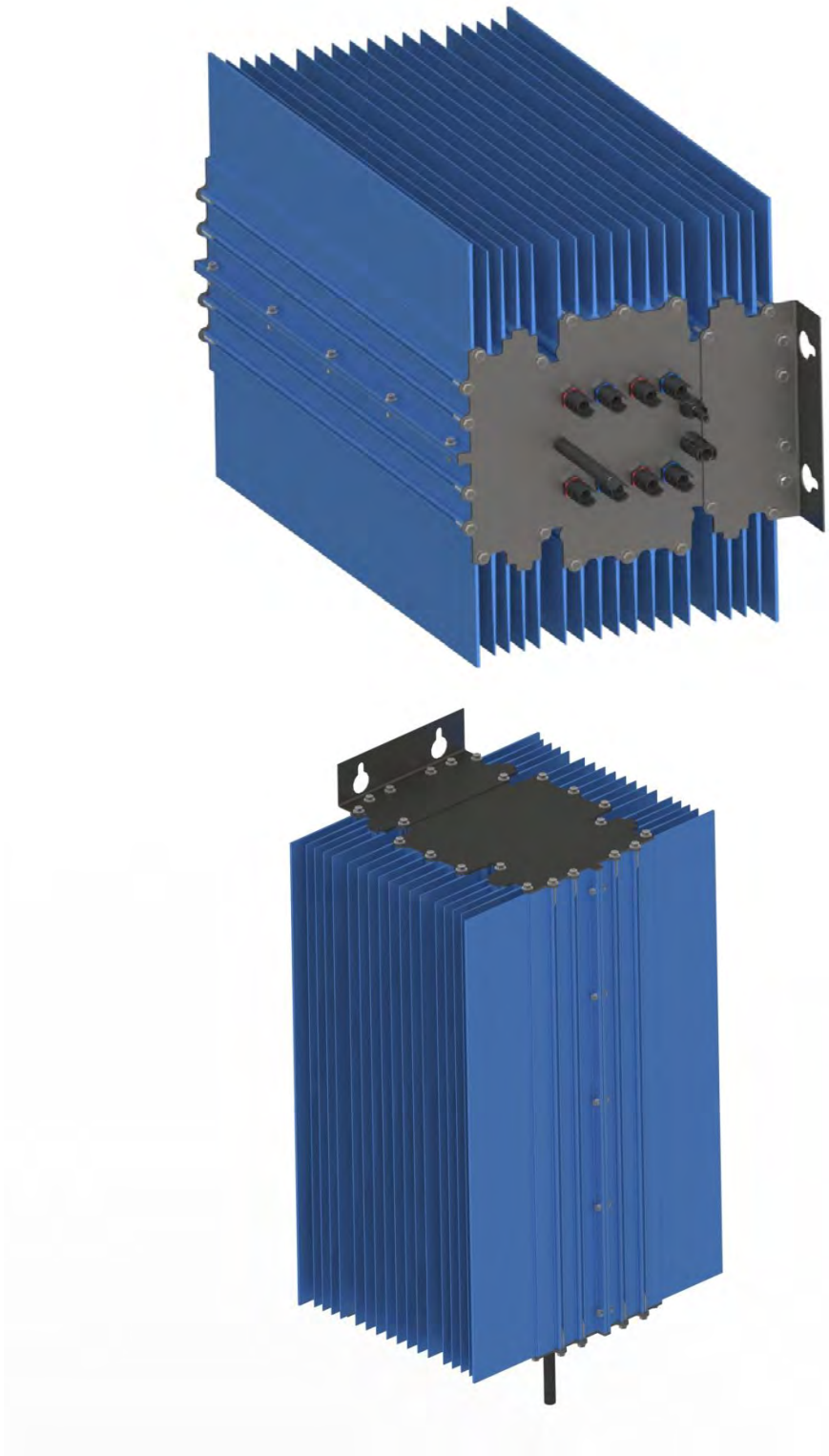


**Figure 96. Production version of SPOT featuring dual custom heat sinks**

Inside the SPOT, the magnetics were redesigned so that the magnetic units would be easily swappable and also reconfigurable. Additionally, the Silicon-Carbide devices were designed to be held against the heat sink via thermal clip, expediting assembly.

Furthermore, the unit was designed to symmetrical top-to-bottom so that it can be easily assembled in two similar halves, and then combined into a single unit by attaching the two units together.

Early in Q1 of 2015, in the process of selecting vendors for components for the final production SPOT, extensive testing of the PPP SPOT revealed a weakness in the driver circuit which caused a particular brand of transistor to fail. With the discovery of this phenomenon, a minor alteration was made to the electrical PCB to improve the robustness of the electrical design. Additionally, provisions for arc detection and ground fault detection were implemented, so as to be fully certifiable as a standalone unit.

The BOM and production drawings for the production version SPOT were sent to suppliers starting in the end of Q4 2014 and concluding in Q2 of 2015, with final assembly of production-version of SPOT expected to be completed in Q2 2015.

#### *5.3.5.3. SubTask 14.3 Perform Reliability Analysis*

A reliability analysis has been completed on all of the components of the GrIP control board, as well as the SPOT control and power boards. This has already created a list of the top longevity offenders on each of the boards, most of which were then able to be replaced in the next iteration of the design. For the analyses, meteorological data from Death Valley, California, were taken to provide worst case estimates in extreme operating conditions for all components.

The SPOT reliability was calculated using available data from component vendors. A report was compiled with the data for continued revision.

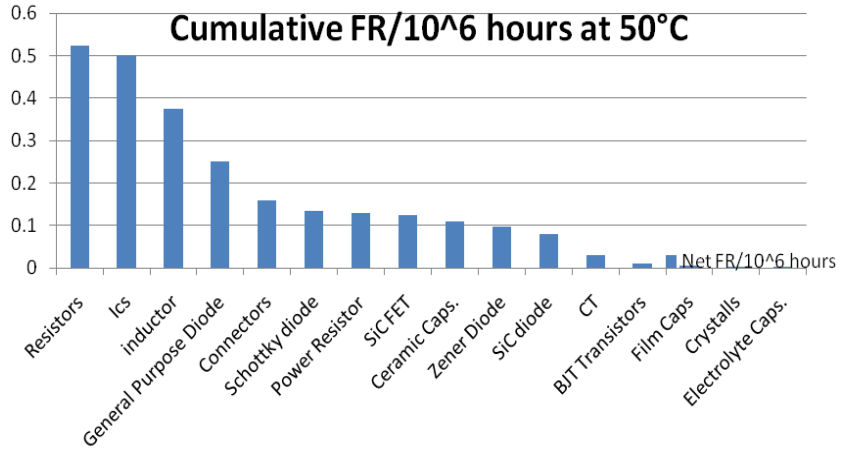



**Figure 97. Distribution of expected rate of failure of different classes of components.**

Features were added to the SPOT in Q2 that will make the Alencon system safer than those using conventional inverters. One example is the distributed ground fault detection and isolation which is only feasible due to the distributed sensing capabilities found with the use of the SPOTs. Though arc-fault detection will not be included in the standard SPOT, a module has been designed to be an optional addition.

#### *5.3.5.4. SubTask 14.4 Demonstrate production readiness*

Production BOMs were completed and locked in for the GrIP, SPOT, and SMC designs. Documentation for the production testing and Q&A were completed as well, with detail growing on the SPOT documentation during interactions with the contract manufacturer. Internal test documents for the calibration of manufactured equipment and testing to UL 1741 and IEEE 1547 standards are in place and ready for when Alencon begins production.

The final BOM for the GrIP totaled approximately XX¢/W, with a majority of the costs lying in the semiconductors and magnetics materials, see Figure 98. Labor constitutes approximately 5% of the costs, while semiconductors amount to 23%, magnetics to 22%. In Alencon's current facilities, the assembly of a GrIP module requires approximately one man week of labor.

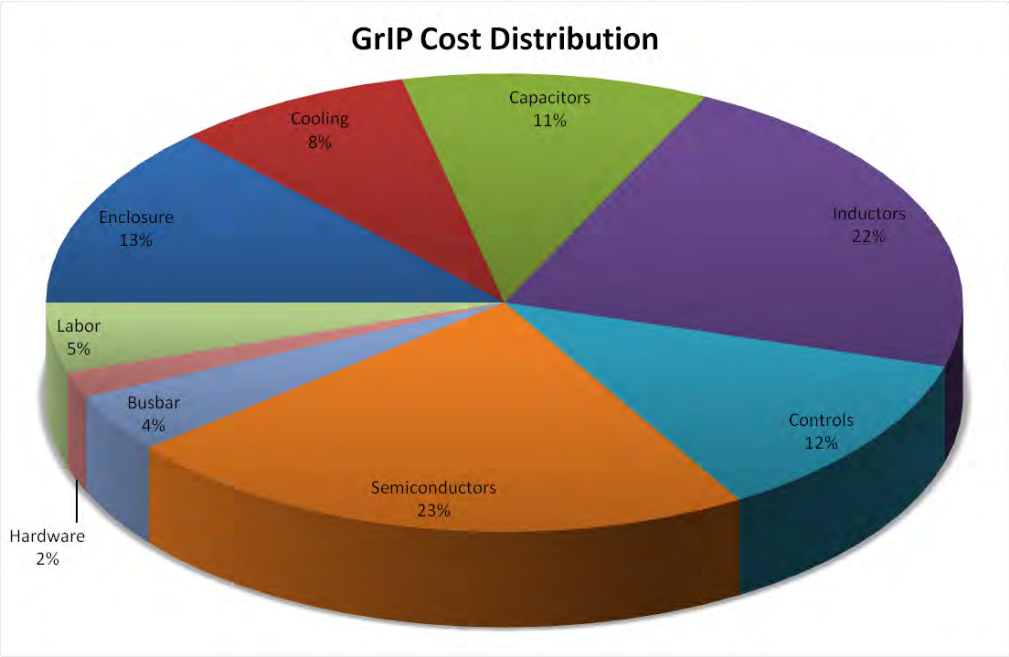



**Figure 98. GrIP BOM Breakdown**

The Dock must, of course, be added to the cost of the GrIP. Current estimates for its costs lie at approximately XX¢/W, with the main power contactors constituting 44% of the total cost, see Figure 99.

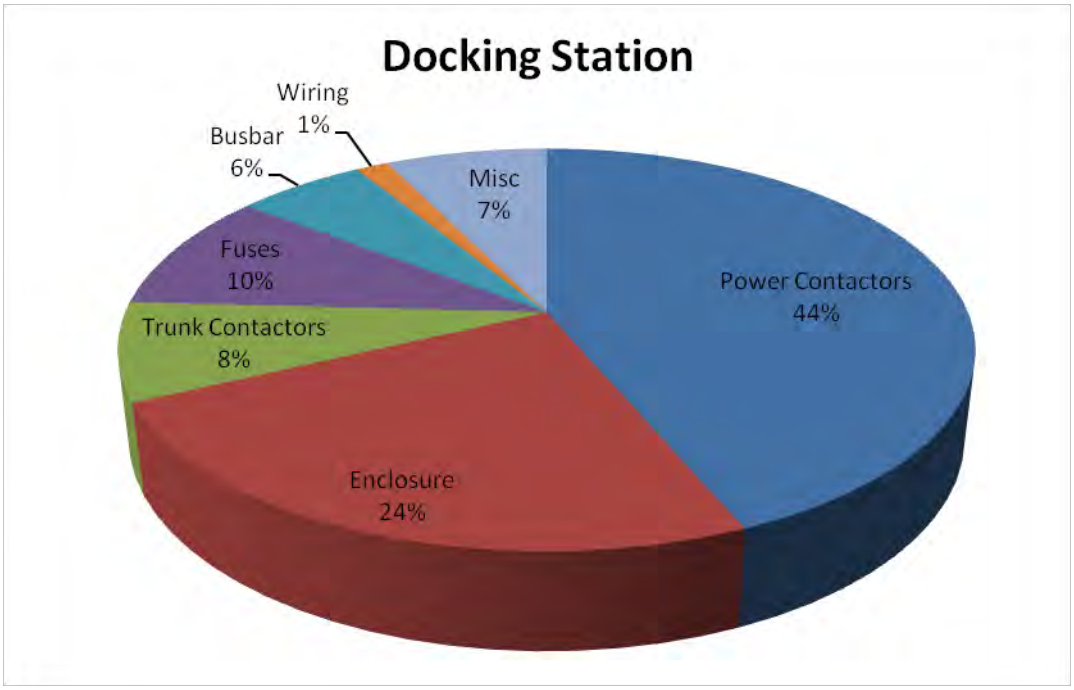



Figure 99. DOCK BOM Breakdown

The BOM for the SPOT is still seeing improvements, especially in that portion which constitutes the largest cost by far. The fairly new Silicon Carbide semiconductors utilized in this device amount to 46% of the cost of the SPOT, see Figure 100.

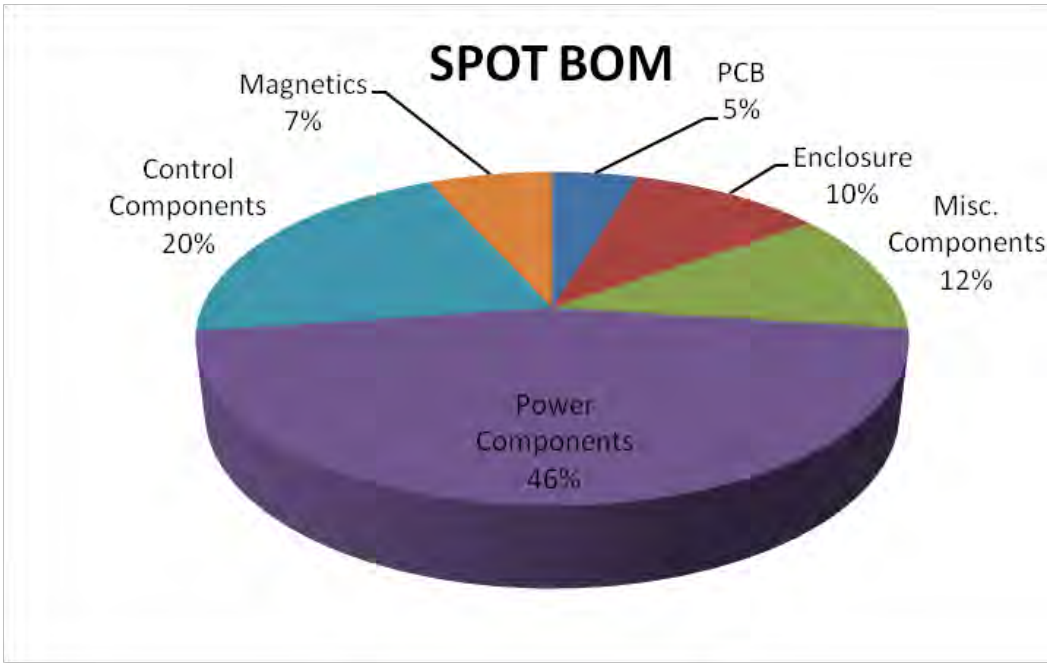



Figure 100. SPOT BOM Breakdown

## 5.4. Final Deliverables

Finalized design of the complete Alencon system meeting all requirements specified in the following:

1. Finalized GrIP design which is ready for production and meets the following targets:
    a. 99% CEC efficiency - Complete
    b. Operation in an inverter system of 4 or more GrIPs - Complete
    c. Operation at 2,500 VDC - Complete
    d. 25 year reliability - Complete
2. Finalized SPOT design which is ready for mass production and meets the following targets:
    a. 99% CEC efficiency - Achieved 98.5% peak 98% CEC weighted efficiency
    b. Operation as a group in the SPOT network - Complete
    c. Operation at 2,500 VDC - Complete
    d. 25 year reliability - Complete
3. Finalized System Master Controller design including all communications interfaces and protocols. - Complete
4. Obtaining certification of the GrIPs, SPOTs, and inverter system. - In progress
5. Completion of the field installation, commissioning and testing of the 400kW beta system including grid interconnection, SPOT, GrIP, and SCADA - In progress
6. Finalized cost/benefits analysis showing overall system cost is less than 10c/W with quantifiable benefits in reduced BOS hardware cost, ease of installation, and increased energy yield. - Complete
7. Final project-close presentation. - Complete

### 5.4.1. BOS Cost Reductions

PV system prices and the various components within them changed drastically throughout the course of this project. When FOA479 was released, utility inverter prices lay around 20¢/W, with 2020 goals set to reduce this to 10¢/W including warranty and smart grid functionality (DE-FOA-0000479). Total system costs were in the $3.80/W range, of which modules constituted 51% of the cost at $1.95/W, BOS $1.34/W, and permitting, taxes, misc., etc. totaling $0.51/W (DE-FOA-0000493). Within the BOS costs, cable and wire added up to 16¢/W.

Today, total system costs are approximately half what they were in 2011. For the average developer, a utility scale plant can be built for ~$1.95/W, with modules in the 70¢/W range. This means BOS and labor costs have finally overtaken modules as the most expensive portion.

Numerous studies to analyze the moving target of PV system costs, and Alencon's effect on them, were completed over the course of the project. The latest compared today's optimal PV system to ascertain very conservative estimates for savings achieved through the use of the new topology. Table 8 gives an overview of the costs and savings from this analysis.

**Table 7. System Cost Reductions**

This table has been omitted for confidentiality reasons.

Most of the savings came from wiring and labor cost reductions, totaling about 80% of the benefit. The XX¢/W reduction in capital investment equals approximately 10% of the BOS costs, as well as being greater than the cost of the power electronics installed in the system. It is important to note that the analysis focused on the savings of very tangible items, such as the reduction in cabling and its associated reduction in labor, that could be precisely attributed to the new approach. Much of the savings we anticipate for the reduction in installation labor for the new approach were not able to be determined exactly.

### 5.4.2. Yield Improvement

The second major benefit of the Alencon approach lies in its efficiency and effectiveness in increasing system yield. The distributed MPPTs, reduced DC (and AC) conduction losses, and high inverter efficiency all add up to a substantial increase in yield over commonplace central inverters.

This report presents a summary of the improvements for each of the major components within the Alencon system. This includes the power electronics on the harvesting system, as well as the.

#### *5.4.2.1. Overview*

For this analysis a hypothetical 10MW AC system was created in PVsyst for both the Alencon and standard (baseline) approach. It would be located along the 21st Latitude in the US, and utilize single axis trackers for racks. The focus of this document will be a few areas that are of interest when attempting to evaluate the benefits of the Alencon topology.

In order to do a comparison, it is very important to look at increases or decreases in yield, which manifest themselves throughout various sections of a system. From the standpoint of efficiency and energy yield, the Alencon system can be viewed as a collection of four segments:

- Harvesting
- DC transmission
- DC-to AC Conversion
- HV transformation

#### *5.4.2.2. Energy Harvesting*

In the Alencon system, each string of modules in a PV system is sourced separately by a SPOT, physically isolating it from the rest of the system. Internal MPPT algorithms assure that a maximum of power is harvested from each individual string, a high granularity which eliminates the possibility of weaker strings (due to shading, degradation, dirt, damage, etc.) to affect the operation of any other string.

SPOTs are mounted in close proximity to the strings minimizing both the length of connecting cables and electrical conduction losses. Each SPOT contains four highly efficient DC-to-DC converters, each serving one of the four strings it sources.

### Degradation Abatement

There are a number of issues that affect PV system output, both immediately upon installation, and over the course of a system's life. This includes module mismatch, degradation, potential induced degradation, delamination, breakage, semiconductor failures, encapsulant failure, and more. Some of these issues can be alleviated

### DC Transmission

SPOTs convert the ~650V string voltage to the 2,500V DC transmission voltage, significantly reducing overall DC transmission losses in utility scale PV systems. Optimized systems can provide conduction losses that reach 0.50% at maximum power, while using no more than 4/0 sized conductors. When compared with standard systems, this can yield reductions in conduction losses between 50-75%.

### Conversion

The DC to AC conversion segment of the Alencon system is based on patent-pending technology that creates quasi-square wave currents, combined with optimal phase shifts that depend on the number of GrIPs in the system. Currents from all GrIPs are summed in harmonic neutralization (HN) transformers, which can also serve as the point of interconnection to the electrical grid. Best practices of industrial multi-megawatt inverters utilized in foundries are incorporated in the GrIP design, such as oversized buses made of oxygen free copper, and liquid cooling for all power components. These techniques drastically reduce switching losses, limit conduction losses, and use only a small number of high capacity, high voltage semiconductors to comprise an inverter system with 99.1% CEC and 99.35% peak efficiency. With the exception of some very large inductors, all components utilized in the manufacture of a GrIP are off the shelf, and total to numbers about one fifth of those in standard inverters.

### Step-up Transformers

Each GrIP creates a three phase 1,750V AC output, with each unit feeding current into a separate set of windings on a HN transformer. The inverter windings could be one of many types, from zig-zag to truncated delta, and are available from almost all major transformer manufacturers.

Depending on the class of high efficiency transformer selected, efficiencies may vary from 99.2% to 99.5% or losses from 0.5% to 0.8%.

### Auxiliary Power

The centralized inverter consisting of several GrIPs will be liquid cooled. With all fans and pumps in full operation, power consumption of the cooling system equates to a negligible 0.015% of the total generated power.

### Total System Efficiency

Total system losses are computed by adding electrical losses in all segments and components of the system. To calculate the total system's effective efficiency, the individual efficiencies of every sub system can simply be multiplied. Table 1 calls out a range of efficiencies and losses for each of the individual portions, for both NOCT (normal operating cell temperature) and maximum power.

**Table 8. System Loss**

This table has been omitted for confidentiality reasons.

#### *5.4.2.3. SPOT MPPT*

### Maximum Power Point Tracking

As mentioned each PV string is monitored and controlled by a separate DC-to-DC converter. Four of these DC-to-DC converters are contained in each SPOT, yet work independently of one another.

Power generated by a healthy PV module depends on the amount of solar irradiance on the module (insolation) and the load applied to its output terminals. The behavior is usually displayed in the manufacturer's datasheets as IV (current - voltage) and PV (power - voltage) curves similar to those shown in Figure 101. Power is a product of voltage and current (P=I*V) and has a peak value called the Maximum Power Point (MPP).

The objective of an MPP tracker is to vary the loading on the PV string to operate at MPP regardless of the amount of insolation - a process called Maximum Power Point Tracking (MPPT). Classical PV systems parallel a number of PV strings and apply the MPPT controls to such a grouped array. Because PV modules are slightly different one from another, the MPP for each group is not normally the sum of MPPs for its member strings. This reduces output of the system, from the potential maximum of MPP sums, usually by 2% to 5%.

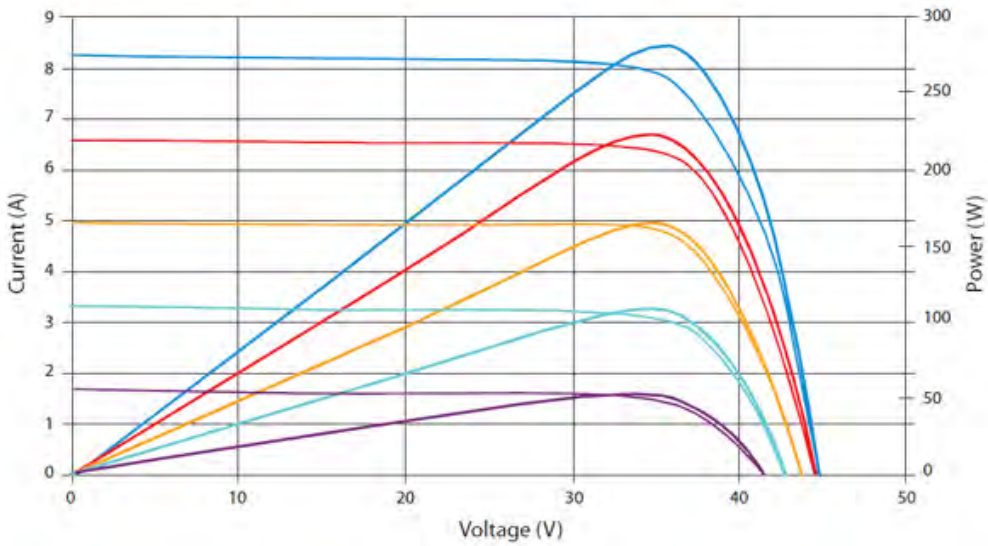



Figure 101. IV and PV curves for STP-280 modules

The situation worsens when some of modules in an array are either shaded, uneven soiling is found throughout the system, or modules become damaged. When this is the case, the IV and PV curves exhibit more irregular features, as seen Figure 102.

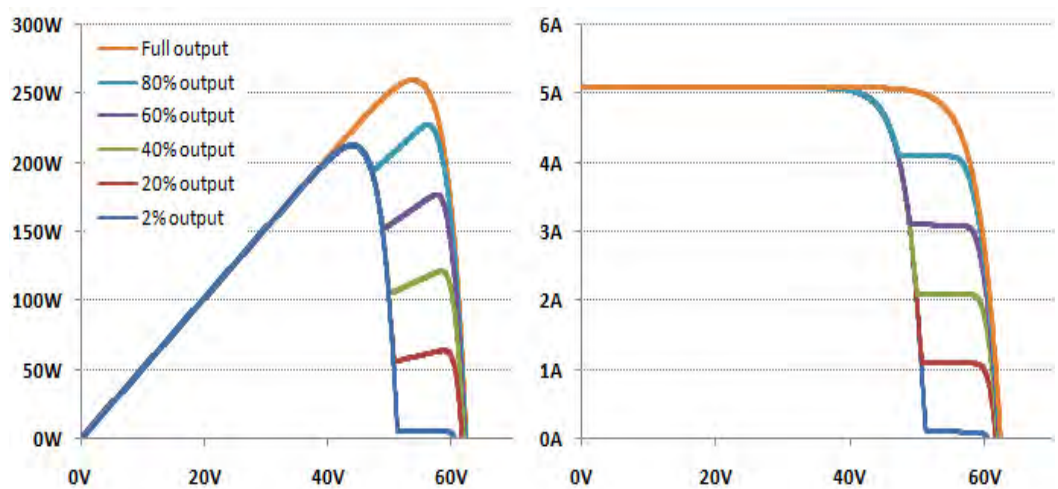



Figure 102. PV and IV curves for a partially shaded example PV module

Shaded modules in strings may actually cause more than one local MPP depending on the shading, at voltages lower than that than of a healthy string. When connected in parallel with fully exposed strings, this heavily affects the overall power production of the string, or when blocking diodes are present even block output from the shaded string completely. Therefore classical systems can produce substantially less power than possible when partially shaded strings are present.

### String-wise MPPT with SPOTs

Each SPOT samples the voltage and current of a string simultaneously in order to avoid measurement skew. These analog values are digitized to compute a power value with the onboard microprocessor. The load seen by the string can be varied by changing the frequency of the resonance inverter, as explained in the SPOT overview, thus it is possible to adjust the voltage and current that is harvested until the MPP is reached. This process can be optimized based on historical performance, neighboring values, etc., giving an adaptive control system that will be able to quickly adjust to regular or unexpected events.

The controls for individual strings will not only benefit healthy, fully illuminated strings, but also reduce the effects of partially shaded, dust covered or damaged strings. Additionally, by implementing adaptive and historic techniques, diagnostics can be made automatically to determine the state of various strings, potentially identifying abnormally shaded strings, or even damage and dust cover.

### System Production Analysis

In order to allow for the effective comparison of two different PV system topologies, various modeling software exists on the market today. PVsyst, with its extensive list of modules and inverters, as well as shading analysis capabilities, was chosen as the main tool for this project. Much of the benefit of the Alencon system would come from the addition of the SPOT on the harvesting section of the system. By giving greater granularity in MPP tracking through individualized control of each string of modules, several improvements in overall system performance become possible.

### Module Mismatch

The most predictable variable that creates loss in the system is that of module mismatch. No PV modules can ever be said to be exactly identical, with module manufacturers' specifications for nominal power, voltage or current ratings generally having a given tolerance of plus or minus several percentage points. Though such discrepancies between modules may at first seem minor, the overall effect on system yield can be significant.

PV module behavior can in many ways be likened to the operation of batteries, especially in their operation in parallel with one another. Standard PV systems place a large number of strings (30-50+) in parallel, and discrepancies in individual characteristics, such as with voltage differences between batteries in parallel, have an effect on overall output. The MPPT at the inverter side selects the point at which the group, on average as a whole, performs the best. This behavior prohibits individual strings from providing the maximum of power that they are able to muster, in some cases even eliminating some from contributing at all. The losses in system performance associated with the discrepancies caused by physical module differences, not shading, etc., are commonly known as mismatch losses.

Two things can be done to alleviate the situation: Exactly matching modules and strings based on real performance, and/or providing MPPTs for smaller groups of strings. The former is currently already used as much as it can be, but is only of limited usefulness in today's large scale systems since very large numbers of modules (up to 1,000+) will have to be grouped together in batches from the factory. With Alencon SPOTs, both these approaches can be taken advantage of; accurately grouping modules into

strings ~20 modules at a time, while extracting a maximum of energy from each of these groups based on their own performance characteristics.

### Degradation and Mismatch

Degradation in the output power of PV modules over the course of a system's lifetime is a well known effect. Most c-Si modules usually show about 0.5% of reductions in output power per year, a loss that is mostly associated with the current produced by the module. Little or nothing can be done about this effect, as degradation is a natural part of the lifecycle of any product.

However, as modules degrade their properties tend to change, and not uniformly so. It has been shown that as modules age their power probability density function will also change, actually widening with time. This means that as modules in a system degrade, the probability that their outputs will match is lowered. Put in other terms, the longer a system is in production, the higher the mismatch losses will be. Figure 103 provides a visual representation of this effect, with module outputs beginning at ±1% of the rating, and increasing to nearly ±5% of degraded power of that year.

What is important to note is that percent mismatch power losses are not equal to the percent mismatch in modules, due to the fact that the area on the I-V curve of a module around the MPP is relatively flat. For example, a 1% mismatch will cause no more than 0.3% in losses. However, over the course of the lifetime of a system, this widening range can add up to a significant loss of income.

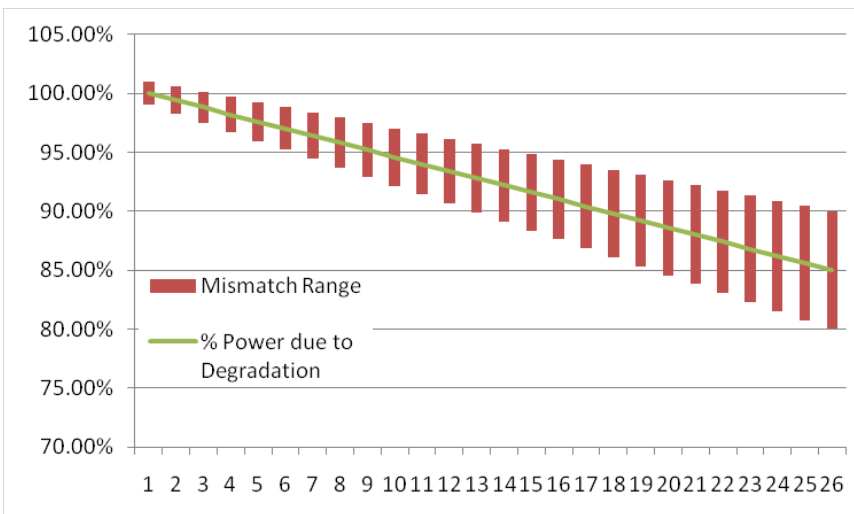



**Figure 103. Degradation and Mismatch over 25 years, with degradation of 0.5%/year and mismatch beginning at ±1%**

### Partial Shading & Operational Differences

Since partial shading on modules and other differences in the performance of strings create discrepancies as those described above, individualized MPPTs help to blunt the impact of these negative effects as well. Ranging from inter-row shading, cloud cover and local obstructions to dust and dirt cover, only shading is predictable and capable of being modeled. Though the effects of shading are generally less frequent, they have a far greater impact on total production in standard systems. Through individualized MPP tracking, the affected strings are effectively isolated from influencing the

performance of the rest of the system. Dust and dirt cover have an effect nearly identical to that of module mismatch, but is not easily predicted and can be alleviated through regular cleaning of collector surfaces.

### Estimates with PVsyst

As a means of comparing the production of the baseline system and that of the Alencon variety, PVsyst was chosen to simulate the generation of each. Sadly the software package did not yet include a number of features that could help quantify the benefits of having string-wise MPPTs. Though the program provides the capability of creating a detailed 3D model for a shading analysis, the implementation only provides reductions in yield on the module side, and does not provide more detailed modeling on the equipment (inverter) side. Though options exist to specify a number of MPPTs to be utilized in the system, varying this number does not reduce the modeled effects of mismatch, partial shading, etc. and thus does not affect overall output. Moreover, a users is left wanting for options to include DC to DC converters, string-side MPPTs and other non-standard system topologies. This may have been addressed in the latest PVsyst release, which we did not have on hand at this time.

For this reason the only method available to create a comparable Alencon system was to begin with the PVsyst output for the baseline system, and manually incorporate the losses or benefits of the Alencon system along the way. The losses associated with the key parts of the system were previously described, which will be included below. Figure 104 gives the output of the baseline model, up to the module quality losses.

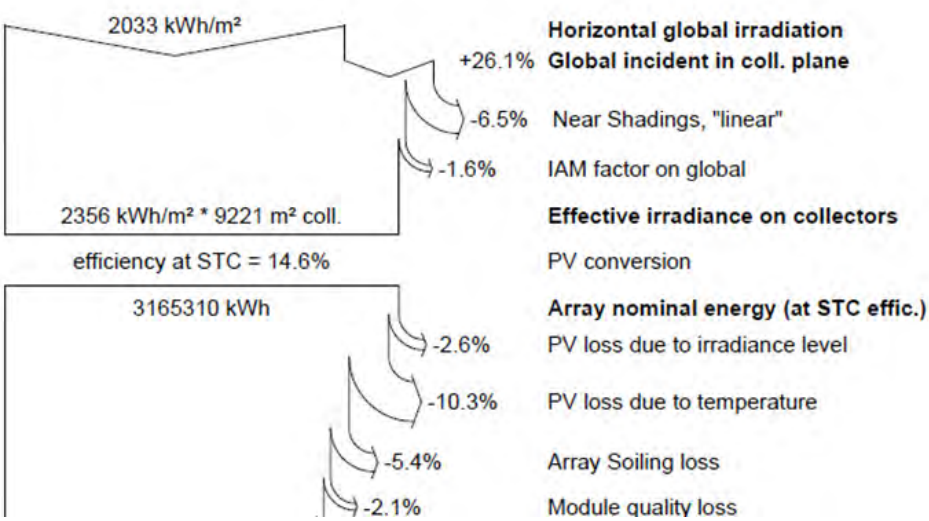



**Figure 104. PVsyst Loss Estimates for a 1.33MW DC (~1MW AC) baseline system**

Though the baseline system only constitutes a ~1MW AC capacity, its numbers will remain the same when several of these are placed together. For the Alencon system, the numbers generated in PVsyst for this 1MW system will be adjusted with the estimates of a 10MW system. The main values to be scrutinized and modified are detailed below.

1. Array Mismatch Losses - PVsyst essentially takes a fixed percentage that the user can input for module mismatch, and subtracts this from the total system production. Claims from various micro inverter companies give mismatch values between 2 and 5%, thus the 2% approximation in PVsyst may be conservative. In the Alencon system, it is safe to assume that these can be minimized, strings can be preordered from the factory in small groups, and individual strings are isolated from others in the system. The model does not provide an increase in this value over time, as would be the case in reality. An analysis of this topic will follow.
2. DC/DC Losses - The portion of losses not included in the baseline estimates associated with utilization of SPOTs will have to be included. As mentioned these amount to approximately 1%.
3. Wiring Losses - Again, PVsyst allows for the user to enter a fixed percentage, or make rough estimates based on selected cable gauge, as well as estimated current and cable length. The highlighted (default) value is not a good approximation in this case, as most large scale PV systems today average conduction losses of at least 2%. Therefore a detailed comparative analysis was done on both the Alencon and standard system. This data will be included herein.
4. Conversion Losses - These are determined entirely by the inverter selected in PVsyst. With the Alencon GrIP providing efficiencies of over 99%, these would amount to no more than 1%.
5. AC wiring losses - With the baseline, an AC ohmic loss of 0.8% was provided as default. This occurs due to the fact that several 1MW inverter stations will be strewn throughout the PV system, finally to be tied together at some point on the outskirts to be combined and stepped up to the main grid voltage. For Alencon these losses will be negligible, as the centralized inverter station can be placed in the vicinity of the final step-up transformer. Cables for systems over 40kV can be direct buried, meaning that even if final step-up transformers are utilized, metering can be placed closely to the conversion station.
6. Transformer Losses - The transformers sourced thus far show that losses on these of 5MVA+ size can be specified as at least 0.5%. If the interconnection is to be completed in two voltage steps, the baseline and Alencon system are expected to have roughly equal losses for this section.
7. Table 10 includes the baseline losses broken down in Figure 104, as well as the most optimal substitutes in the Alencon system. Losses for the SPOT are offset by the benefit of having string-wise MPPT, giving an approximately 1% performance increase versus standard systems.

**Table 9. Breakdown of PVsyst Loss Diagram at NOCT**

| Loss | Baseline | Alencon (optimized) |
|---|---|---|
| Temp, Soiling, etc. | 20.4% | 20.4% |
| Non-degradation Mismatch | 2.5% | 0.9% |
| Wiring Loss | 1.68% | 0.52% |
| SPOTs | 0.0% | -1.2% |
| Inverter | 1.5% | 0.9% |
| AC Ohmic Loss | 0.8% | 0.1% |
| Transformer Loss | 1.0% | 0.5% |
| Total | 27.88% | 22.32% |

By analyzing the losses in Table 10 it is possible to assign energy production estimates after each successive step, see Table 11, and finally end with an estimated total yearly production for each approach. After the step-up transformers, the Alencon baseline system production totals approximately 151MWh more than the baseline.

**Table 10. Adjusted PVsyst production values following each incremental loss**

| | | Production (kWh per year) | |
|---|---|---|---|
| | | **Baseline** | **Alencon** |
| | Modules | | |
| | Temp, Soiling, etc. | 2,519,587 | 2,519,587 |
| | Mismatch | 2,456,597 | 2,496,910 |
| After: | DC Wiring | 2,415,326 | 2,483,927 |
| | SPOTs | 2,415,326 | 2,513,784 |
| | Inverter | 2,378,724 | 2,486,187 |
| | AC Wiring | 2,343,292 | 2,483,701 |
| | Transformers | 2,319,859 | 2,471,158 |

## Estimated yield & production

To estimate the total yield of the system at a given location, it is necessary to divide the total energy produced by the overall capacity of the system. This provides a kWh/kW value which can be used in straight forward comparisons that actually incorporate the entirety of this analysis. Table 4 provides these for both the baseline and Alencon systems.

**Table 11. Estimated yield based on Table 11 as well as Alencon upside**

| | **Baseline** | **Alencon** |
|---|---|---|
| | 1,744 | 1,858 |
| **Difference** | | 6.54% |

This kWh/kW value shows that the Alencon systems benefit from a 6-7% increase in production per kW per year.

However, it is important to note that the values estimated here were taken to be as very conservative. String-wise MPP tracking would provide additional unaccounted benefits during times of shading, as well as over time with the effects of degradation taking hold. It is possible to estimate these losses, using what has been described as a guideline.

With a few assumptions, a rough monetary value can be placed on the generated energy. For example, with an electricity rate of $0.06/kWh, Figure 105 shows the production value of 10MW AC systems over 25 years, using the above kWh/kW and including the estimated mismatch gains for Alencon.

Analyzing each of these curves and estimating their net present value (NPV) with a 6% discount rate, we can infer the value in either ¢/kWh or ¢/W installed. Table 13 shows the total increase in value that the Alencon approach provides.

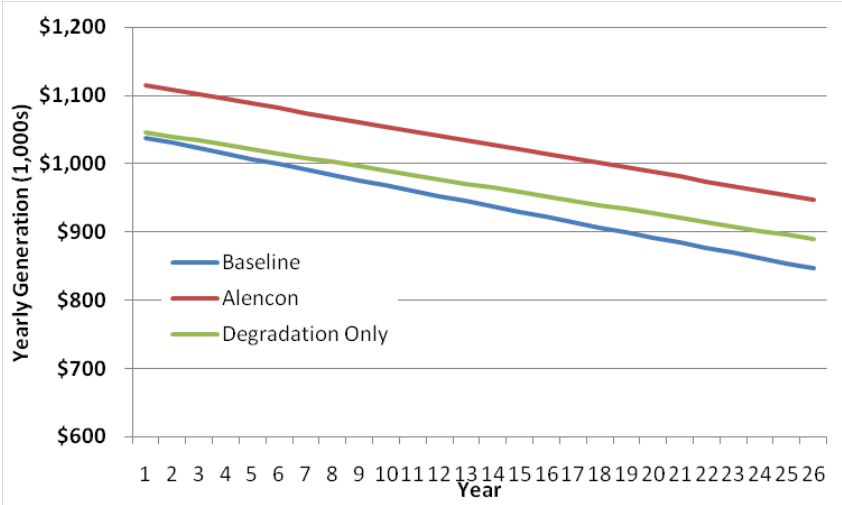



**Figure 105. Production comparison of the baseline and Alencon systems, as well as a hypothetical system without module mismatch losses (green).**

**Table 12. Value Analysis**

| | Baseline | Alencon | Without Module Mismatch |
|---|---|---|---|
| Sum total: | $ 24,483,105.94 | $ 26,810,940.00 | $ 25,165,920.00 |
| NPV @ 6%: | $ 12,559,534.77 | $ 13,683,451.67 | $ 12,843,885.75 |
| **Percentage NPV:** | **100%** | **108.95%** | **102.26%** |

As can be seen, when approaching the subject purely from a yield perspective, ignoring hardware and other up-front cost savings, the topology already makes for a compelling argument.

## Summary

The conservative analysis, including only the benefits of yield and efficiency increases provided by the Alencon topology, already shows a gain of nearly 9% in value over the course of the systems lifetime. Additional up-front savings in conductor costs, labor, engineering, etc., are not included and provide another boon for adopters.

### 5.4.3. Path Forward

The remaining tasks that have not yet been completed include the certification of the equipment, and the installation of the beta site. Certification for the GrIP is under way, with the mechanical design review nearing its completion. A preliminary review for the SPOT was completed, with the mechanical design review to follow. Testing on the SPOT will begin after the completion of internal testing, which will begin when the first set of production SPOTs are received in mid to late April. Certifications are anticipated to be completed in Q3 of 2015.

The construction of the beta site can begin once the first 25 production SPOTs are received from the contract manufacturer. This will happen once the first samples are tested and approved by Alencon, and is anticipated in Q2 of 2015.

These two items will prove very valuable for commercialization efforts, and will mark the beginning of a period of heavy marketing and sales efforts. Manufacturing for the SPOTs will be done through a contract manufacturer, with sampled testing to be done in house at Alencon. GrIP assembly will be completed by Alencon in house, with the expansion into a larger manufacturing space to follow a ramp up on production.

## 5.5. Patents and Publications

The company filed for various patents for technology developed in this project. Though filed for before the start of the project, they provide pertinent information that may be useful in gaining a greater understanding of the novel approaches taken herein.

**Table 13. Multiphase Grid Synchronized Regulated Current Source Inverter Systems**

| Jurisdiction | Application Serial No. | Current Status | Patent No. |
|---|---|---|---|
| United States | 12/325,187 | Granted | US 8,130,518 B2 |
| United States | 12/542,891 | Granted | 8,213,199 B2 |
| Australia | 334024 | Granted | AU 2008334024 B2 |
| China | 200880125924.7 | Pending | |
| Europe | 8857360.5 | Pending | |
| Israel | 204998 | Pending | |
| India | 1340/MUMNP/2010 | Pending | |
| Japan | 2010-536212 | Pending | |
| Korea | 10-2010-7012215 | Pending | |

**Table 14. Collection of electric power from renewable energy sources via high voltage, direct current systems with conversion and supply to an alternating current transmission network**

| Jurisdiction | Application Serial No. | Current Status | Patent No. |
|---|---|---|---|
| United States | 12/543,338 | Granted | US 8,212,408 B2 |

**Table 15. High Voltage Energy Harvesting and Conversion Renewable Energy Utility Size Electric Power Systems and Visual Monitoring and Control Systems for Said Systems (First Concept)**

| Jurisdiction | Application Serial No. | Current Status |
|---|---|---|
| United States | 13/253,629 | Pending |
| Australia | 2011 312098 | Pending |
| China | 201180058480.1 | Pending |
| Europe | 11831527.4 | Pending |
| Israel | 225609 | Pending |
| India | 809/MUMNP/2013 | Pending |
| Japan | 2013-532919 | Pending |
| Korea | 10-2013-7011410 | Pending |

**Table 16. Second Solar Power Optimizer and Transmitter Concept**

| Jurisdiction | Application Serial No. | Current Status |
|---|---|---|
| United States | 14/116,783 | Pending |
| Australia | (to be assigned) | Pending |
| China | (to be assigned) | Pending |
| Europe | (to be assigned) | Pending |
| Israel | 229333 | Pending |
| India | (to be assigned) | Pending |
| Japan | (to be assigned) | Pending |
| Korea | (to be assigned) | Pending |

**Table 17. Third Solar Power Optimizer and Transmitter Concept**

| Jurisdiction | Application Serial No. | Current Status |
|---|---|---|
| United States | 13/892,271 | Pending |

# 6. Conclusion

The project started with a basic prototype for the inverter module, and a conceptual design for the DC/DC converter. From this starting point, several iterations of prototypes were completed for both products. The addition of a system master controller to orchestrate the operation of the system as a whole, and an innovative method for visualizing data collected through various communication channels rounded out the solution.

Additionally, over the course of the project, Alencon built an excellent team of engineers from scratch, and achieving just about every highly aggressive goal defined at the beginning of the project. This technology will reduce LCOE costs by approximately 10-15% when compared to today's optimal system, and power electronics costs pushed to well below the original 10¢/W goal.

With ever more pressure being placed on the power electronics employed in renewable energy systems, Alencon is confident that the technology developed with help of this SunShot award will be of great value to the industry. The company is now getting ready to commercialize its products.