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INTERIM/FINAL PROJECT REPORT

Maximum Power Point Tracker Inverter for Photovoltaic Systems with Energy Storage and Dispatchability

Prepared for: California Energy Commission
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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Maximum Power Point Tracker Inverter for Photovoltaic Systems With Energy Storage and Dispatchability is the final report for the SMUD ReGen project (Contract Number 500-00-034), conducted by SMA America. The information from this report contributes to PIER's Renewable Energy Technologies program.

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For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

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Abstract

This project developed an inverter that dispatches power to the utility from battery storage systems., While connected to an electrical grid, the inverter also functions as a maximum power point tracking photovoltaic inverter, which is an inverter that converts the variable direct current output of the photovoltaic modules into frequency alternating current that can be fed to the electric grid using the maximum possible power from the photovoltaic array. Additionally, the inverter can function as back-up power during grid failures. These functions may be controlled locally or by remote devices.

The inverter is the first residential distributed generation product to combine the functions most wanted by the homeowner (high efficiency grid-tied photovoltaic and back-up power) with those wanted by the California Energy Commission and California utility companies (grid-support with stored battery power).

Throughout the development of the inverter, the market requirements shifted. The rolling blackouts of 2001 initially created a strong demand for back-up power. Since then the grid has remained relatively stable, and interest in back-up power systems has waned. Utility companies are still interested in distributed means of grid-support; however, they have not determined how this technology will be implemented. This next step will require a concerted effort to develop a unified standard of control and functional requirements for manufacturers to follow.

Keywords: Solar, photovoltaic, PV, PV inverter, dispatchability, back-up power, stored battery power

Executive Summary

Introduction

Under the Public Interest Energy Research contract, SMA America developed a Maximum Power Point Tracker Inverter for photovoltaic systems with energy storage and dispatchability. The project developed an inverter that dispatches power to the utility from battery storage systems, while also functioning as a Maximum Power Point Tracking Photovoltaic Inverter when the grid is present. The inverter can be used as a back-up power source during grid failures.

Purpose

Many home owners realize that their grid-tied photovoltaic systems are not designed to operate during grid outages, as conventional grid-tied inverters lack energy storage (usually in the form of batteries). An inverter specifically designed to isolate from the failed utility grid and support local electrical loads is needed. Existing inverters that perform this function usually operate very inefficiently when connected to the grid. The solution that SMA proposed was a combination of a high-efficiency grid-tied photovoltaic inverter and a battery back-up inverter in one simple topology (formation). This inverter would require a new topology design and special software to control the different operating modes.

With the support and funding from the Energy Commission, SMA America developed a multifunction consumer product meeting today's market requirements, with advanced utility functions to meet tomorrow's utility requirements. The inverter is the first residential distributed generation product to combine the functions most wanted by the homeowner (high-efficiency, grid-tied photovoltaic system interconnection and back-up power) with those wanted by the Energy Commission and California utility companies (grid-support with stored battery power).

Project Objectives

The primary objectives of the project were to:

- Develop a cost-competitive single-stage inverter topology capable of battery charging from the grid, incorporating photovoltaic maximum power point tracking, and dispatching power from the battery to the grid.
- Develop and demonstrate the feasibility of remote dispatch capability for distributed renewable power systems with storage abilities.
- Increase the overall inverter efficiency compared to existing grid-tied battery based inverters to the levels found in dedicated grid-tied photovoltaic inverters.
- Reduce overall system costs by reducing the balance-of-system components compared to existing back-up power systems.

- Simplify the installation of a multi-mode power system, further reducing overall system cost.

Project Outcomes

Throughout the course of addressing the specific objectives of the inverter project, the following outcomes were achieved:

- The inverter demonstrated a successful design, utilizing a single-stage inverter topology capable of battery charging from the grid, incorporating photovoltaic maximum power point tracking, and dispatching power from the battery to the grid. The design topology for the inverter was specifically chosen to meet these three technical requirements as well as the market requirements for a multi-function photovoltaic and battery back-up inverter. The majority of the time the inverter would be converting PV power to the grid. During a grid outage, the inverter would be used to support local electrical loads from the battery.

- Remote dispatch capability for renewable power systems was realized in concept. The inverter contained the ability to dispatch power to the grid from the battery from a remote location with no renewable energy source feeding the battery. The basic concept of delivering power from a battery to a utility is available and fully functional within the SMA inverter. However, the feasibility of doing so became questionable as the project evolved.

- The project team successfully developed a simple method for remotely controlling the inverter to dispatch power to the grid. The control could be a Personal Computer with 802.11x wireless, radio, cellular, or any form of hard-wired or radio communication.

- The project team successfully increased overall inverter efficiency. The baseline study of existing inverters from other manufacturers of battery back-up and Photovoltaic grid-tied inverters showed instantaneous efficiencies of 69 percent and overall energy capture efficiencies of 55 percent. The inverter instantaneous and overall efficiencies were found to be almost identical at 92 percent each.

- Combining each functional element of a back-up power and a grid-tied system into one device allowed a reduction in wiring and interconnection components, resulting in reduced overall system cost by approximately 50 percent compared to similar systems that integrate multiple single-function devices.

- Since there are fewer components to install, labor costs are significantly reduced. Labor is the second highest cost of any photovoltaic system, second to the cost of the Photovoltaic panels. Simplifying system installation has a dramatic effect on the overall system cost. Labor costs for the inverter are reduced by approximately 25 percent when considering just the labor for installing the inverter(s) and balance-of-system components.

Conclusions

The inverter is a development that will become the basis for a family of battery-based inverters to be developed by SMA over the next two to three years. The first product in this family, the Sunny Island 4248U, was released in the summer of 2004. The Sunny Island 4248U incorporated the basic back-up power and battery management developed under this project. Future developments will incorporate the advanced functions of the inverter (dispatchability and direct photovoltaic grid-tied functions).

Recommendations

Based on the developments throughout the course of the project and the conclusions above, the project team recommends the following:

- The dispatch function was one of the main technical aspects of the inverter research project. Unfortunately, how to implement this function was not considered. For future research projects, some detail should be considered at the onset of the project to help identify any technical or contractual issues that could affect a critical project task.
- It was very difficult to find a test location since the inverter was not Underwriter's Laboratory (UL) listed. SMA's field test period was drastically shortened. It took many months for Sacramento Municipal Utility District's legal department to approve a test site and then many more to prepare the site for the inverter. For future projects, locating an acceptable test site earlier in the project process will improve the quality and duration of the field testing.

Benefits to California

The inverter is crucial to developing an advanced SMA back-up power system that incorporates grid-tied photovoltaic and allows exporting of stored power to the grid. From the development of the inverter, SMA has developed a basic back-up power system called the Sunny Island 4248U. This product was introduced to the California market in summer 2004. Further developments are underway to integrate the dispatch function into the battery management system and also integrate photovoltaic into the system. These functions will be released over the next two to three years in advanced versions of the Sunny Island.

The market for back-up power systems is expected to increase if energy prices continue to increase and if grid reliability decreases. Utility companies will then continue to increase time-of-use and peak-support charges to their customers. The Sunny Island family of products will be well positioned in this energy market. SMA is already seeing interest in a product that can dispatch power from stored energy sources to counter California's load peaks, either in short duration (starting of a large motor) or long duration (afternoon air-conditioning loads). A future version of the Sunny Island will monitor the building load demand and supplement utility power when peak loads and surge support is needed.

The PIER project has provided SMA the means to develop these advanced Sunny Island functions that will provide the California energy market with products needed in the coming years.

1.0 Introduction

Distributed Generation (DG) has become a popular subject among power system planners in the last decade. The radial distribution systems developed during the last 100 years are no longer able to support the widely spread energy demands of quickly growing population centers, such as California. New large, central-station power plants and their support infrastructures are difficult to site, are sometimes too costly for today's market, and many of the environmental impacts are no longer acceptable to the general public. Relatively few new central-station power plants have been installed, yet energy demands continue to grow at alarming rates.

This inverter was developed with the support of the California Energy Commission to prove that existing distributed power sources in the form of residential back-up power systems could be used to help support the existing utility infrastructure during periods of peak demands and reduce the threat of rolling blackouts.

1.1 Background and Overview

The California rolling blackouts in 2001 prompted utility companies and the California Energy Commission to explore alternative means of power production. One option was to explore the possibility of using existing back-up power sources to generate power during times that the grid neared maximum capacity. The premium cost of this form of power could be justified during these times. Given the distributed nature of the physical locations of the generation, the utility distribution system might not require any updates or additional infrastructure. One form of existing generation is residential battery back-up power systems.

The rolling blackouts also prompted California homeowners to explore options for reliable back-up power, especially homeowners with existing PV systems. Utility grids in populated areas are generally quite stable, making back-up power systems seldom necessary. Most urban homeowners decided that the inconvenience caused by infrequent and short-term power outages did not justify the cost of back-up power systems. However, during the rolling blackouts of 2001, these same homeowners realized their grid-tied PV systems were useless during a blackout, as they were not designed to operate during grid disturbances. They became very interested in making their PV systems operate in a back-up power mode. At the time, this would have required some form of energy storage (usually batteries) and an additional inverter specifically designed to isolate from the failed utility grid and support their local electrical loads. It would also require a reconfiguration of their existing PV array in order to charge the batteries properly. There was no ideal product that could perform both tasks, even though the technology for both functions was almost identical. There were products available that were combinations of different technologies, and some were packaged as kits (often do-it-yourself kits). These products proved expensive, difficult to install and configure, unreliable, and inefficient. The ideal solution

was a combination of a high-efficiency grid-tied PV inverter and a battery back-up inverter in one simple inverter topology. This inverter would require a new circuit topology design and special software to control the different operating modes.

This new inverter design could also be used to generate or 'dispatch' power to the utility from the battery during times the grid reached maximum capacity. This would require some additional hardware changes and further software development. In theory, the utility company or the California Independent System Operator (CAL-ISO) would be able to command these systems to turn on as necessary. Combining all of these functions into one highly efficient, low cost inverter became the concept of this project, Maximum Power Point Tracker (MPPT) Inverter for PV Systems with energy storage and dispatchability, for dispatching power to the utility grid.

1.2 Project Objectives

The primary objectives of this PIER project involved:

1. Developing a low cost, grid-feeding inverter incorporating both the maximum power point tracking functions and backup power capabilities with an overall energy conversion efficiency of 90%.
2. Developing remote dispatch capability for renewable power systems.

The dispatch capabilities were to be demonstrated in field trials to verify the effectiveness of customer sited renewable power systems as an energy management tool.

By integrating the functions of a grid-tied PV inverter with a battery back-up inverter, and providing a remote controllable dispatch function, the equipment owner and the utility company will have a new product to supply emergency grid support and distributed generation. This product would better meet the needs of the California consumer and thereby accelerate the widespread adoption of renewable energy systems in the State.

1.2.1 Technical Objectives

SMA America met the technical objectives of the inverter project, including:

1. Developed a single-stage bridge topology capable of battery charging from the grid, incorporating PV MPPT to the grid, and dispatching power from the battery to the grid.
2. Demonstrated the feasibility of dispatchable power from distributed storage sources.
3. Developed a method for remotely controlling the inverter to dispatch power to the grid.
4. Increased the overall inverter efficiency compared to existing grid-tied battery based inverters to the levels found in dedicated grid-tied PV inverters. Baseline

systems were instrumented and compared to measured results from the final product testing.

All functional requirements of the inverter were assembled in a physical housing, with a single inverter bridge and controller. Overall energy efficiencies were increased to approximately 90%, as compared to 55% from a Xantrex SW5548 grid-tied PV inverter and battery back-up system. The SMA inverter can be controlled locally or remotely via a PC interface that can be easily adapted to any form of remote wireless interface.

1.2.2 Financial Objectives:

SMA America met the economic objectives of the inverter project, including:

1. Reduced the specific cost of the inverter package to a level similar to that found in grid-tied PV inverters. Combining all the functional elements of a back-up power and a grid-tied system into one device reduced the overall system cost by approximately 30% compared to similar systems that integrate multiple single-function devices.

2. Reduced overall system costs by reducing the balance-of-system components compared to existing back-up power systems. The total major component count was reduced from two inverters to one inverter, while reducing required accessories (switches, breakers, terminal blocks, wiring, etc.) which were integrated into the inverter.

3. Simplified installation of a multi-mode power system, further reducing overall system cost. Since there are fewer components to install, labor costs are significantly reduced.

1.3 Report Organization

Section 2 of this report describes the details of the initial data gathering for a benchmark to existing technology, design considerations, and project development. Section 3 summarizes the outcomes and results of the project. Section 4 provides project conclusions and recommendations as well as benefits to the State of California.

2.0 Project Approach

SMA America saw the opportunities of the PIER project to develop a new class of inverter for the California market that could also meet future requirements of the utility companies. The development of a single-stage, multi-function inverter is new to the renewable power industry. Furthermore, the ability to dispatch stored back-up energy to the utility from a remote location further advanced the features of this design.

The basic approach of the project tasks is structured in a typical engineering project: specification, prototype construction, testing and final construction, and field testing. Peripheral tasks (communication interfaces and control software) have been broken out as separate tasks. The order of the subsequent sections is similar to the deliverable tasks outlined in the original project schedule.

2.1 Existing Inverter Baseline Performance Investigation

To better understand the performance of existing technologies at the start of this project, it is decided to monitor existing installations with similar performance features that would be found in this inverter. There are a small number of California systems that have both PV grid-tied and back-up power capabilities. At the start of this project, these systems were composed entirely of Trace Engineering (currently Xantrex Technologies) SW-GTI 5548 inverters. These systems incorporated a PV array, battery bank, DC to AC battery inverter, a PV to battery charge controller, a special utility interface module between the inverter and the utility grid, and a variety of special switchgear and protection equipment.

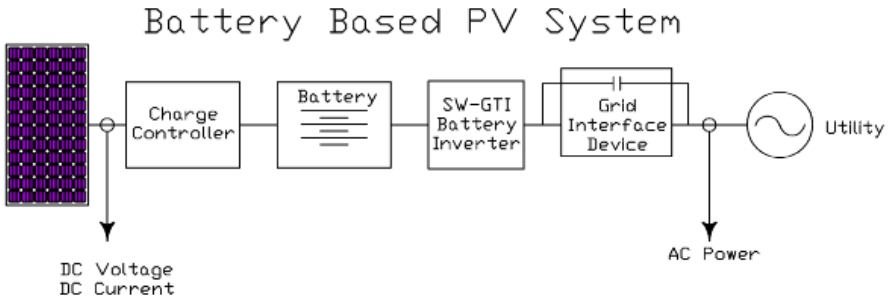


Figure 2.1 Block diagram of a SW-GTI battery based PV system

Photo Credit: SMA America; Photo Credit: Xantrex Technologies

These systems are intended to serve as a grid-tied PV inverter when the utility is present. When the utility failed, the system would isolate from the utility and begin powering several of the local loads from the battery. It is commonly known that most of the available PV energy was consumed by the inverter to maintain a full state-of-charge on the battery. At night, the system continually consumed utility power to maintain a full state-of-charge on the battery. These systems were also very inefficient when the sun was shining as the battery charging requirements prevented a MPPT to be utilized.

Figure 2.2 SW-GTI 5548 grid-tied/backup system components

Photo Credit: SMA America

To understand and quantify the overall energy efficiency of the SW-GTI, SMA installed data acquisition systems (DAS) on two nearby systems. The DAS measured and recorded power from the PV array, power to the battery, and the power to and from the utility grid. By comparing the power from the PV array to the utility power, the authors were able to quantify instantaneous inverter efficiency as well as overall system energy efficiency.

Data was collected for 12 months revealed:

- The instantaneous efficiency: 69%
- Overall energy capture efficiency: 55%

Direct grid-tied systems available at the time were producing 92 to 94% instantaneous efficiency. The SW-GTI 5548 had two conversion stages between the PV array and the grid. It also had an inaccurate power tracker, poor DC current regulator, and continuously float charged the batteries. These three things combined resulted in a poor instantaneous efficiency.

Similarly, at night the SW-GTI 5548 continued to float charging the batteries, consuming a large portion of the energy that was produced from the PV array during the day. Recent research has shown that battery life expectancy is significantly reduced when continuously charged. The plots below show typical day(s) of net energy production and instantaneous power output from the inverter.

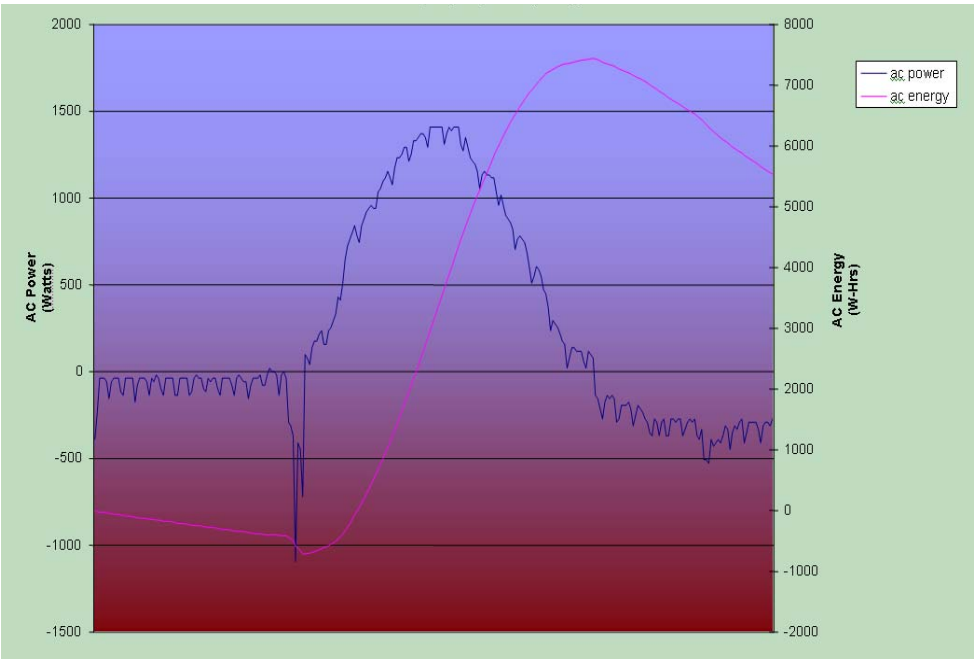


Figure 2.3 Typical day, net energy production and instantaneous power output from the SW5548 inverter

Photo Credit: SMA America

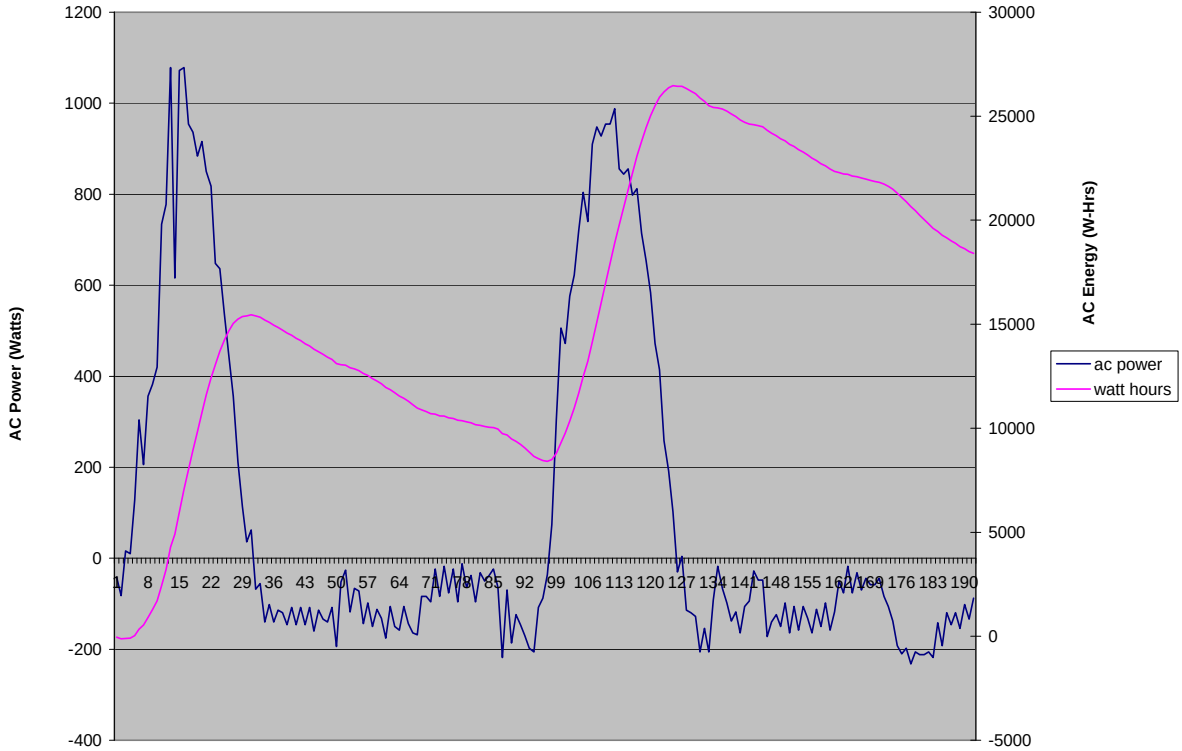


Figure 2.4 Typical AC power and Watt-hours from the SW5548 inverter (2-day period)

Photo Credit: SMA America

2.2 Inverter Platform Requirements

The first step was to write a detailed technical specification describing how the inverter should operate. This document was reviewed by SMA engineers and went through a series of revisions. From this technical specification, more detailed internal documents were created detailing the software and hardware requirements. Hardware drawings, schematics and software flow charts were generated based upon the details of the technical specification. Frequent changes were made to the general specification as the first prototype was developed.

2.2.1 Inverter Topology Options

The most important aspect of the inverter specification was deciding on an inverter topology. The topology is the basic schematic of the power stage of the inverter. The choice of topologies dictates the type of inverter, the efficiency, and the power sources that can be connected to the input of the inverter. There are numerous choices available, all of which involve a series of tradeoffs between flexibility, cost, simplicity, and performance. SMA simplified the decision down to three possible topologies.

Inverter Architecture Option 1

This topology basically operates either from the battery or the PV array. When the grid is present, the inverter is processing PV power to the grid with an efficiency rating similar to that of a fixed, grid-tied inverter. The battery is normally disconnected with the state-of-charge monitored by the inverter. The battery is charged from the grid when necessary. If the grid fails, the inverter switches to a battery based inverter, isolates itself from the grid, and powers the local loads with battery power. The PV array is connected directly to the battery when PV power is available. The PV array is also connected directly to the battery when the inverter is dispatching power to the grid.

The disadvantage to this topology is the PV power is not utilized at the peak-power-point of the array when the grid is not present or during dispatch. This trade-off is acceptable because the majority of the time the grid will be present. PV power is delivered to the grid at the PV peak-power point and at high inverter efficiency.

The advantage to this topology is the same power stage hardware may be used since both the PV and battery voltages and currents are similar. This keeps the inverter cost low, part count low, reliability high, and efficiency during normal operation high.

Advantages:

- High conversion efficiency from PV to the grid
- Simplified battery management control
- Minimum hardware cost
- Simplified installation (single enclosure)

- Low voltage PV and battery.

Disadvantages:

- No MPPT when charging the battery.
- High DC currents due to low voltage PV and battery.

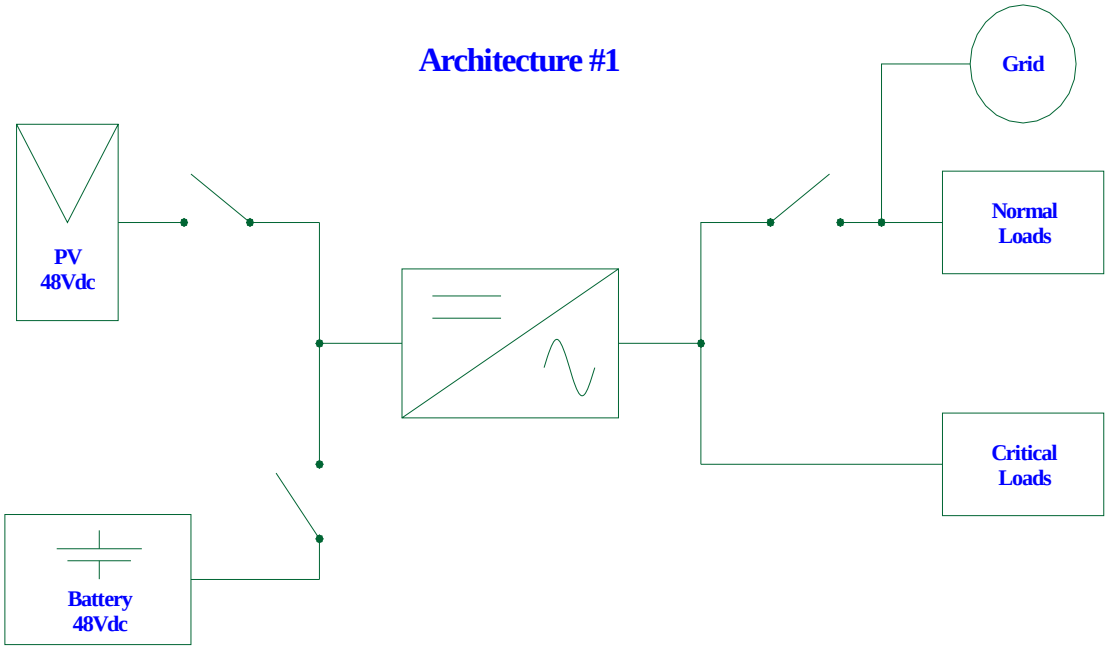


Figure 2.5 Block diagram of inverter architecture No. 1

Photo Credit: SMA America

Inverter Architecture Option 2

This option is the typical topology for battery-based PV systems (it is the same topology found in the SW-GTI). All PV power is processed through a separate charge controller converter, into the battery, then through the inverter and to the grid. As seen from the performance of the SW-GTI, the throughput efficiency is quite poor. Total cost is also quite high due to the large number of necessary components.

When the grid is present, power from the PV array is delivered to the battery via the external charge controller. The inverter then delivers power from the battery to the grid. This process is the same when dispatching power to the grid. The overall efficiency is low due to losses in the charge controller combined with high losses in the inverter. Conversion efficiency in this inverter topology is low due to high losses when converting low-voltage battery power to a relatively high-voltage grid. A much higher efficiency is achieved when the battery voltage is closely matched to the grid voltage.

When the grid fails, the inverter powers local loads with battery power. The charge controller continues to deliver power to the battery.

The disadvantage to this topology is the high number of parts and components, high complexity and installation cost, and low overall system efficiency in every state of operation.

The only advantage to this topology is the PV array may be operated at the peak-power-point during any state-of-operation.

Advantages:

- Traditional approach familiar to the industry.
- MPPT PV charge controller hardware is available off-the-shelf.
- MPPT battery charging continues when the grid is disconnected.

Disadvantages:

- Much lower efficiency compared to grid-tied PV inverters.
- High battery losses.
- Extended wear and tear on the battery.
- Complex installation and configuration of all components.
- High costs due to many balance-of-system components (disconnect switches, breakers, fuses, interface enclosures, wiring, etc.)
- High DC currents due to low voltage PV and battery.

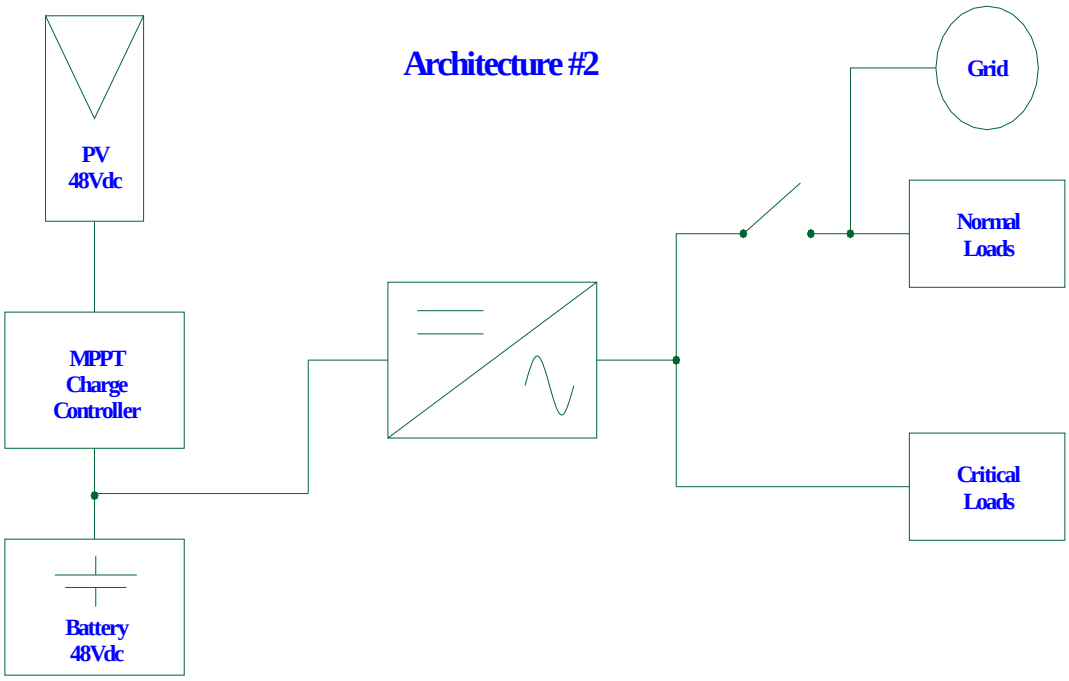


Figure 2.6. Block diagram of inverter architecture No. 2

Figure 2.6 Block diagram of inverter architecture No. 2

Photo Credit: SMA America

Inverter Architecture Option 3

Option 3 allows the interface of a high-voltage PV array and a low-voltage battery to the grid inverter. This allows the use of the same technology available in existing grid-tied PV inverters for grid feeding. Unfortunately, the battery requires a separate battery charge controller stage to convert the power from low-voltage to high-voltage, resulting in high losses to and from the battery.

When the grid is present, power from the PV array is delivered directly to the grid through the inverter. The charge controller maintains the battery state-of-charge. When the grid fails, the inverter powers local loads with battery and PV power. The PV array is always tied directly to the inverter, contributing power when array power is available. During dispatch the inverter delivers power from the PV array and the battery via the charge controller.

This topology yields low total system efficiency due to dual power conversion across the charge controller and the inverter.

The disadvantage to this topology is the high number of parts and components, high complexity and installation cost, and low overall system efficiency in dispatch and battery charge states-of-operation.

The advantage to this topology is high efficiency from the PV array to the grid.

Advantages:

- Low PV current.
- Low battery voltage.
- MPPT when charging the battery.
- High efficiency from PV to the battery.

Disadvantages:

- High battery current.
- Additional battery conversion stage (high losses).
- Communication required between two conversion stages.
- Additional hardware required to support both stages.
- Low efficiency between the battery and the grid.

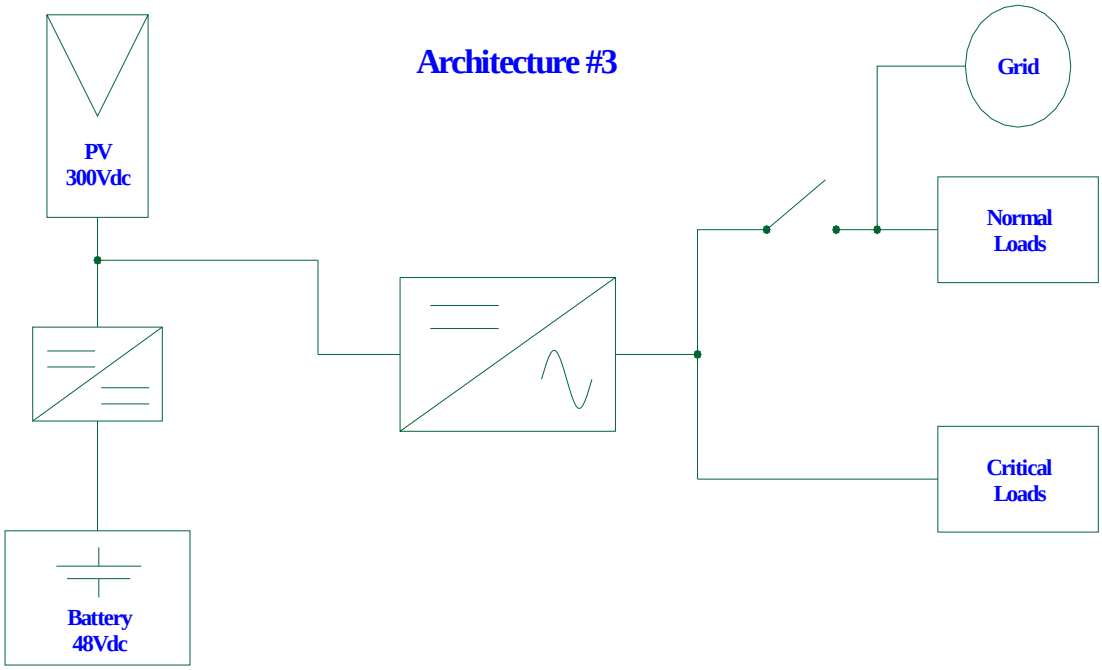


Figure 2.7 Block diagram of inverter architecture No. 3

Photo Credit: SMA America

2.2.2 Inverter Topology Selection

The authors decided to use the approach in Architecture 1. The project team realized that the market for this product was nearly always in a utility territory with infrequent power outages. Therefore, a high-efficiency, PV-to-utility conversion would be important. During an occasional, short-term power outage, it would be acceptable to lose some PV production. This product also had to be cost competitive with existing grid-tied PV inverters; therefore it was necessary to keep the parts count low to keep unit and installation costs down. Architecture 1 was the best solution for the inverter.

2.2.3 Dispatch Function Development

One key aspect of the PIER project was the ability to command the inverter to dispatch power from a remote location. This was called the Dispatch Function (DF). While writing the specification it became clear that the considerations driving the design were not controllable by SMA or its engineering team. The original Statement of Work described the ability to command the inverter to deliver battery power to the grid from a remote location. After some research, it became clear that there was not only no standard for doing this, but there were no utility companies doing anything like this. The closest thing found was FM radio technology used for residential load-shedding relays. Typically, these devices are installed at residences and used to disable air-conditioning units during times of peak utility capacity. It turned out that SMUD used a different technology for this task than Pacific Gas & Electric, which was different from San Diego Gas & Electric. Furthermore,

there was no communication protocol standard for controlling customer distributed generation devices in any manner.

Another difficult issue was how contractual agreements between the equipment owners and the utility companies would be handled. Normally, the inverter would not be affected by this, but in this case it may be necessary to put special control options into the inverter. For instance, the customer may opt to not allow the utility to command their inverter to dispatch power if the battery state-of-charge is not full. There may also need to be special programming for kWh pricing arrangements within the inverter. The customer could choose to only allow energy dispatch if the price per kWh were above a pre-programmed level. Since this system would also act as a back-up power system if the grid failed, the customer would most likely want to have some reserve capacity in the battery after a dispatch cycle. The customer would not be able to support local loads if the utility had already consumed all of the available energy within the battery and then the grid failed. Once these contractual issues were defined, it would be necessary to write special communication protocols to work with the utility company control software.

We approached SMUD's ReGen Program Advisory Committee (RPAC) with this dilemma. It was clear that these issues were outside the scope of this PIER project and outside the jurisdiction of the RPAC. SMA and RPAC agreed that this was a proof-of-concept project and it would be acceptable to provide a simple dry-contact relay input. When this relay was activated, the inverter would begin processing power from the battery and PV array (if available) to the grid. If at some future time, these technical and contractual issues were resolved, the inverter could be adapted to new control requirements.

2.2.4 Remote Inverter Control

The original concept for remote inverter control involved the possibility of long-distance wireless communication for dispatching power to the grid. From the discussions in the previous section, it was not possible to define these requirements at the time of the PIER project. SMA decided to move forward with an active control concept that involved direct communication with the inverter from a PC. SMA integrated a wireless serial technology into the communication link to show that it would be possible to use any number of wireless technologies to control the dispatch functions of the inverter. This isolated the PC control software development from a wireless hardware development that had yet to be defined.

2.2.5 Inverter State Machine

The term *state machine* refers to a control system map for a device that performs functions based upon conditional inputs. For instance, the inverter is designed to transition to the Charge state (charging the battery) when the battery state-of-charge is below a programmed limit, the grid is present, and other conditions exist, etc.

The inverter state machine was designed as part of the technical specification. The state machine was revised numerous times as the inverter was engineered and tested.

Below is the final state machine diagram for the inverter:

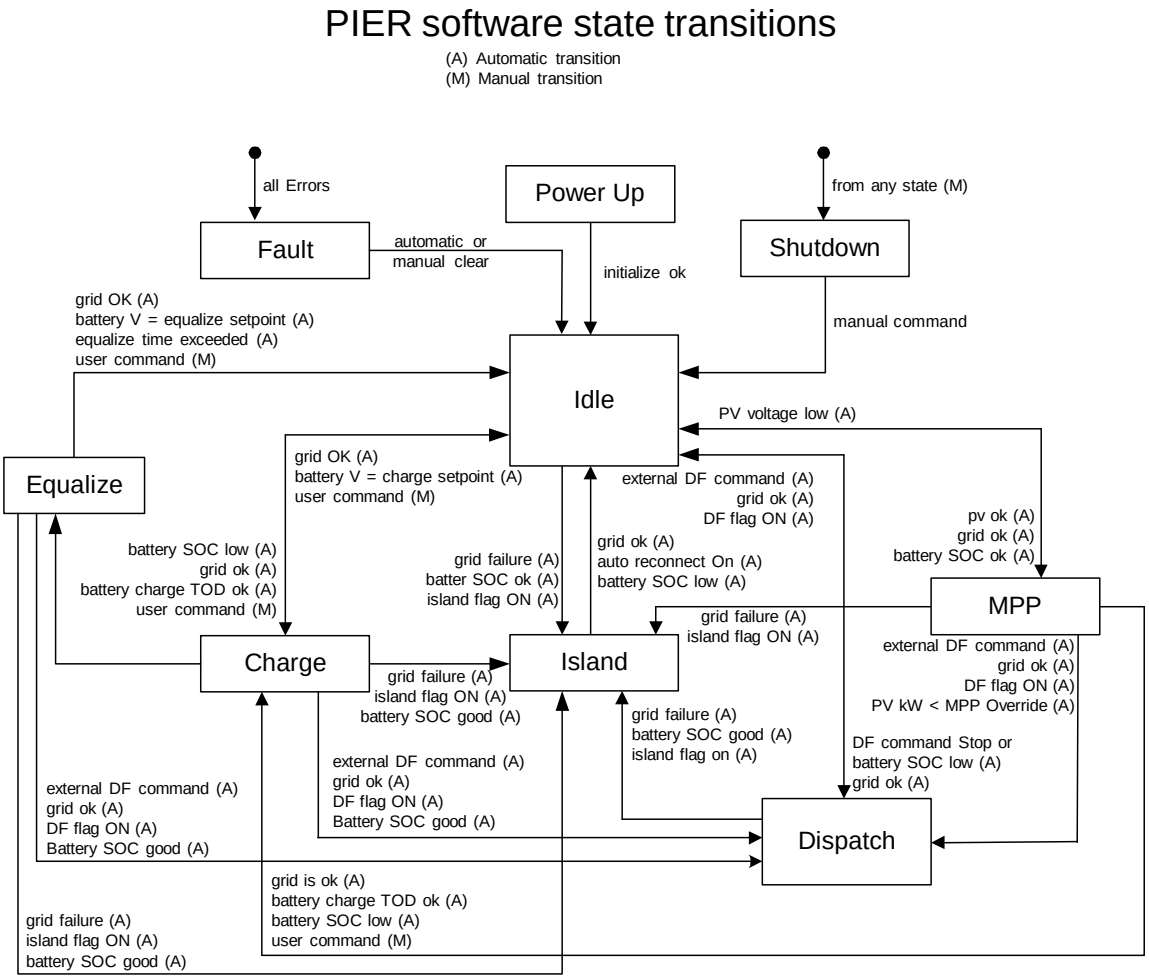


Figure 2.8 State machine diagram for the inverter

Photo Credit: SMA America

Table 2.1 Primary states-of-operation

State	Description of Operation
Idle	Inverter communication only is active. The power stage is inactive with no power being processed through the inverter. All external power relays are opened. The inverter monitors the status of the utility voltage and frequency, PV and battery voltage.
Fault	The inverter has registered a fault and is not operational. Some faults require operator intervention to be reset. Some faults automatically reset, while others are permanently latching and require service.
Power Up	Initialization state of the inverter after control power is applied. The system starts running in a controlled manner, provides system self checks, and verifies the states of all external devices. All external hardware control systems will start in a safe manner.
Shutdown	The Shutdown state is commanded manually from any state. The inverter remains in this state until the user commands the inverter to transition to Idle. The inverter is inoperable in this state.
Charge	The Charge state monitors and maintains the battery state-of-charge. There are various user settable parameters related to the battery charge functions. The battery is actively charged from the grid and passively charge from the PV array when PV array power is available.
Equalize	The Equalize state is very similar to the Charge state. Equalize allows the batteries to be charged to a user settable voltage above the Battery Charge Voltage setpoint. This de-sulfates all cells in the battery, allowing them to hold the same charge voltage.
MPPT	MPPT is the PV Maximum Peak Power Tracking state. The inverter delivers the maximum power available from the PV array directly to the utility grid. In grid tied applications, this is the primary mode of operation. It is not necessary for the PV to charge the battery if the battery state-of-charge is low. If the battery state-of-charge drops below the battery recharge voltage setpoint, the inverter will top off the battery from the grid in a relatively short period of time (see Charge state for more detail).
Island	The Island state is a voltage source mode of operation. The inverter maintains an opened grid-isolation contactor, isolating itself and the local loads from the grid. It supports the loads by supplying voltage and current as demanded. The inverter continues to monitor the utility side of the isolation contactor. If the grid is present and within allowable voltage and frequency range, the inverter will synchronize and reconnect to the grid. The user has the ability to override automatic grid-reconnect.
Dispatch	The Dispatch state manages power delivery from the battery to the utility.

	This state is designed for grid support when the utility power capacity nears its capacity limit. An external command is broadcasted to the inverter, requesting it to export stored battery energy to the utility grid. This may be commanded from the local or remote user interface. Power is delivered at a rate set by the DF Power Limit parameter.

Photo Credit: SMA America

2.2.6 Inverter Operating Parameters

There are many user settable operating parameters within the inverter control firmware. Many of these parameters govern the transitions within the inverter state machine (*Section 2.2.5 Inverter State Machine*). A complete list of these parameters, their settings, and descriptions may be found in the Appendices of this report.

2.3. Inverter Construction

Construction began on the prototype inverter after the initial inverter specification was completed. As with any electronics project, it was necessary to make many changes to the original specification as the hardware and firmware were developed. Weekly meetings were held with the developers to evaluate progress, answer design questions, and agree on necessary engineering changes as they developed.

The first inverter was constructed and used to verify functionality of the hardware and firmware, thermal stability, control system stability, and state machine operation. Once the authors were comfortable that the platform was stable and functional, work began on the next units to be used in the field testing.

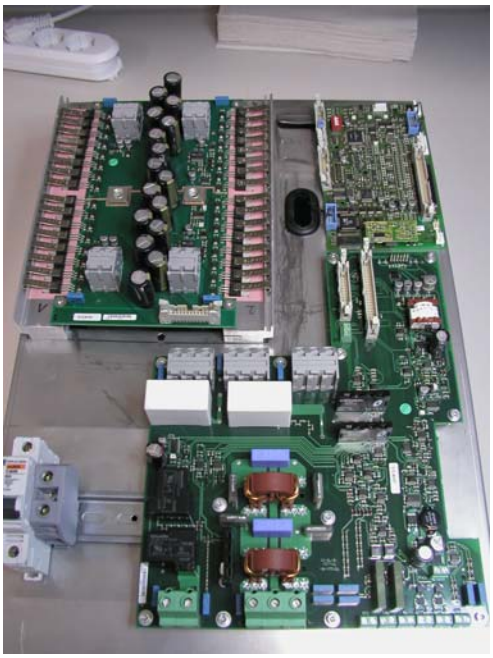


Figure 2.9. Pictures of the inverter early prototype

Photo Credit: SMA America

2.4 Field Testing of the Prototype Inverter

After the original prototype was finished, work began on four new inverters for field beta testing. The original plan was to install these at sites within SMUD territory where SW-GTI inverters were installed. Data would be gathered to determine how well the inverters performed compared to the SW systems. Unfortunately, SMUD determined that since these inverters were not UL listed, SMA could not install them within the SMUD service territory.

The only site deemed acceptable to install a non-UL listed product was at the SMUD Hedge Substation which was considered "behind-the-fence." The next step was to locate an acceptable low-voltage PV array at the Hedge Substation, and then SMUD needed to install a utility meter for the inverter. The inverter was installed on a small Powerlight roofing-tile array and then connected to the grid. The Powerlight array was also part of the PIER program. Powerlight installed DAS metering equipment on their array and also on the output of the inverter. SMA installed a DAS system on this inverter to measure performance. Due to several site delays, the authors were forced to reduce our testing period to a few months rather than a complete year.

On September 22, 2004, this inverter was installed at the SMUD Hedge Substation. The inverter was left operating in an automatic mode, which included PV MPPT, battery charge regulation and back-up power to site loads during utility outages.

The inverter was tested with:

- Eight (8) T105 Trojan deep-cycle batteries, in a 48V configuration.
- Approximately 1,100 W PTC of Powerlight poly-crystalline PV panels, configured in 60 V strings.
- Site loads consisted of four 40 W fluorescent overhead shop-lights, and a temperature controlled attic fan, and two wall plug outlets for additional loads. These loads were connected to the isolated output terminal of the inverter.

The inverter was directly monitored by an SMA Sunny Boy Control data acquisition system, which recorded internal inverter states, errors, and operating data. The inverter was also being indirectly monitored by a Powerlight DAS system, which recorded the inverter AC power output, PV array temperature and weather data.

Figure 2.10. The inverter test site at SMUD's Hedge Substation

Photo Credit: SMA America

Figure 2.11 Theinverter Hedge test site installation

Photo Credit: SMA America

The inverter operated for a period of six months. Data was periodically gathered from the DAS system and used in performance reports submitted to SMUD. During the times the batteries were in an acceptable state of charge, the inverter peak-power-tracked the PV array in the same manner as a normal grid tied inverter.

The following figure shows the inverter power tracking the array over the period of two days. The PV voltage is shown in blue (darker, squared off line) and the AC power output is shown in magenta (lighter, curved bell shaped line).

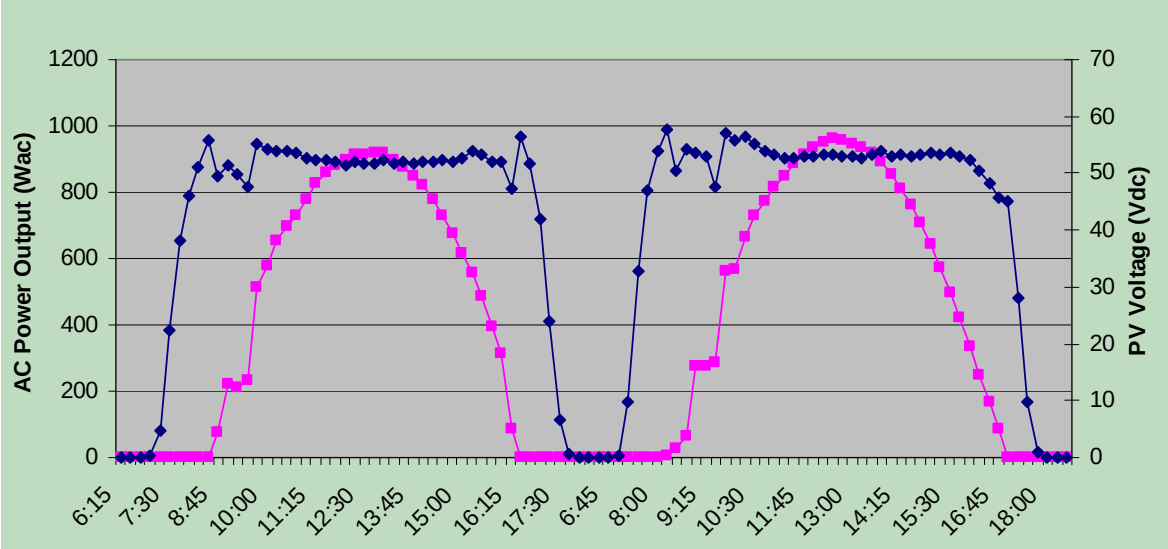


Figure 2.12 Typical 48 hour MPPT period—Hedge test site

Photo Credit: SMA America

The batteries connected to the system had rather low capacity and exercised the charge routines every two to three weeks. This showed the control system was operating properly over the period of testing. The following plot shows battery voltage across a three-hour charge cycle.

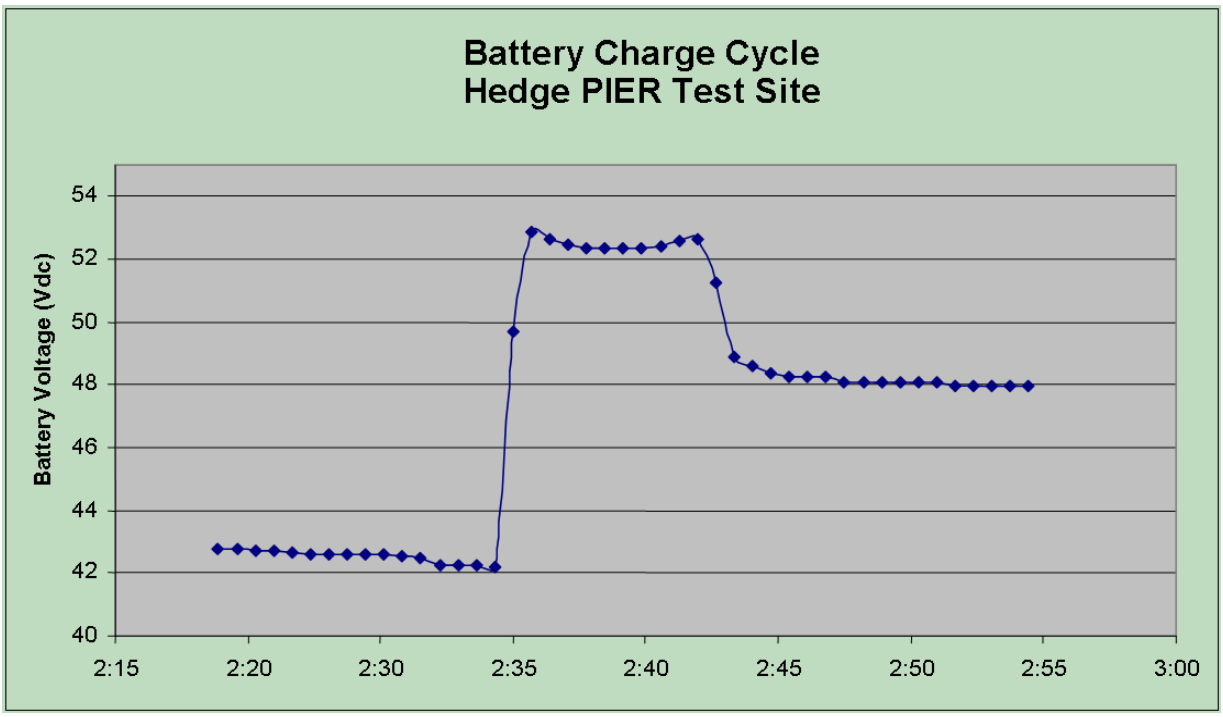


Figure 2.13 Typical battery charge cycle—Hedge test site

Photo Credit: SMA America

The following plot shows AC power to and from the inverter over a two-day period, including a charge cycle. The inverter outputs power to the grid from the PV array during the day and at night consumes a small amount of grid power to charge the battery.

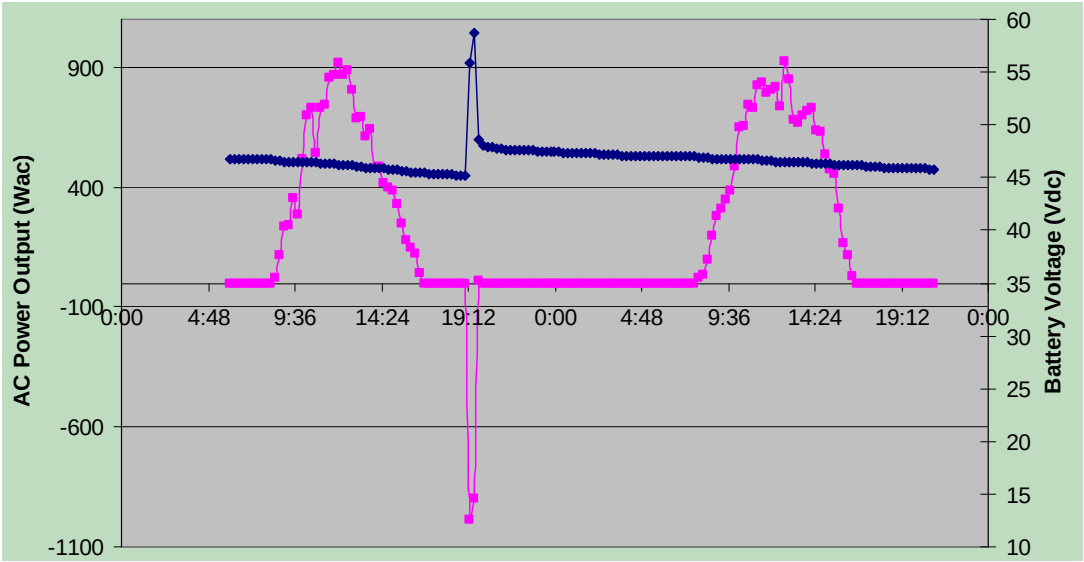


Figure 2.14 Inverter power profile (showing charge cycle)—two days

Photo Credit: SMA America

2.5 UL Testing

The original Statement of Work included a task for UL listing of the inverter. After discussions with the RPAC, it was decided that the task of UL listing would not be warranted. The inverter was clearly a proof-of-concept project, one that the renewable energy market was not ready for. The Dispatch Function was not a feature that was desirable since it was not clear how it would be implemented with various utility companies.

The inverter technology developed in this project will certainly be used in future grid-tied inverter designs with battery back-up capability. Portions of the hardware designs and firmware routines developed in this inverter have already been integrated into the Sunny Island 4248U back-up power inverter that was launched in the United States marketplace in 2004. Subsequent revisions of this design will incorporate the ability to grid-feed low voltage PV arrays and batteries directly to the grid. The concept for grid-feeding batteries and the Dispatch Function are quite similar. The only difference is the execution of the command to begin delivering power from battery storage to the grid during periods of peak utility capacity. It will be quite simple to integrate the Dispatch Function if future demand develops.

2.6 Inverter Dispatch Function Development

The task to develop the Dispatch Function (DF) was, in principal, rather basic. A dry-contact relay input was included in the inverter. When this relay was activated by an outside source, the inverter was to transition to exporting power to the grid, presumably from the battery. The implementation of how this state actually operated was more complicated. For instance, if the inverter was already MPPT the PV array at a high power level, it made no sense to stop power tracking and switch to using energy from the batteries. Therefore, a number of special configurable control parameters for the DF were integrated in the inverter control system. Some of these were added as basic features a typical equipment owner would want. These features were considered from the equipment owner's perspective, rather than the utility company. In principal, the utility company could control these parameters with a direct communication link to the inverter, if the equipment owner allowed access. These issues would need to be negotiated at the time of interconnection and contractual agreements between the equipment owner and the utility company or power broker agency.

Refer to section 2.2.3 Dispatch Function for background on the evolution of the Dispatch Function (DF) in the inverter.

2.6.1 Dispatch Function Parameters

The following parameters were included in the inverter control systems. These parameters could be modified via the interface program used to also command the inverter to transition to Dispatch mode.

There are many other parameters used to control the inverter, some of which are interrelated to the DF parameters.

Table 2.2 Dispatch function parameter summary table

Function	Range	Units	Default
DF Enable	0 or 1	N/A	1
DF MPPT Override	0 to 2500	Watts	2200
DF Bat Low Volt Lim	40 to 60	Volts DC	48
DF Bat Low Volt Recover Lim	0 to 10	Volts	2
DF Pwr Lim	0 to 2500	Watts	2500

2.6.2 Description of Dispatch Function Parameters

- **DF Enable:** Setting the flag to 1 allows the inverter to be commanded remotely into Dispatch mode.
- **DF MPPT Override:** If the inverter is power tracking the array at a power level greater than the DF MPPT Override setting, it will continue to power track the array. If the PV power drops below this setting, the inverter will transition to DF and export power from the battery. This ensures that battery power will not be wasted if there is acceptable PV power available.
- **DF Battery Low Volt Lim:** This parameter sets the threshold where the inverter will cease exporting DF power from the battery. With this set point, the equipment owner may reserve battery capacity in the event the grid fails during a DF cycle.
- **DF Battery Low Volt Recover Lim:** This is a battery hysteresis recovery parameter, which precludes the inverter from cycling back into DF after the DF Battery Low Volt Lim has been reached.
- **DF Pwr Lim:** This sets the export power limit of the inverter when dispatching power to the grid.

2.6.3 Typical Dispatch Function Operating Scenario

The following is an example illustrating the function of DF parameters:

Table 2.3 Dispatch function parameters and settings

Parameter	Setting
DF Enable	1
DF MPPT Override	2,000 W
DF Bat Low Volt Lim	43

DF Bat Low Volt Recover Lim	1.5
DF Power Lim	2,500

In this scenario, the inverter is operating in MPPT mode and delivering 1,500 Watts to the utility grid. Battery voltage is at 47 Volts. The inverter receives the DF command and stops the MPPT and transitions to DF (the PV array is now directly connected to the battery, supplying some power into the battery, less than the MPPT amount). The inverter delivers 2,500 W of power from the battery to the utility grid until the battery voltage falls below 43 V. The inverter then stops exporting power from the battery to the grid and transitions back to MPPT. The battery voltage recovers from 43 to 44 V and holds.

2.7 Dispatch Function Control from a PC

A control program was developed in order to control the inverter from a remote location. This program was created especially for this inverter. The program incorporated an SMA proprietary serial communication protocol. From a standard PC, a user could:

- Monitor the real-time functions of the inverter
- Modify inverter operating parameters
- Change operating states of the inverter (command the inverter to Dispatch mode)

Below are screen shots from the PC interface program:

Table 2.4 The inverter parameter list summary

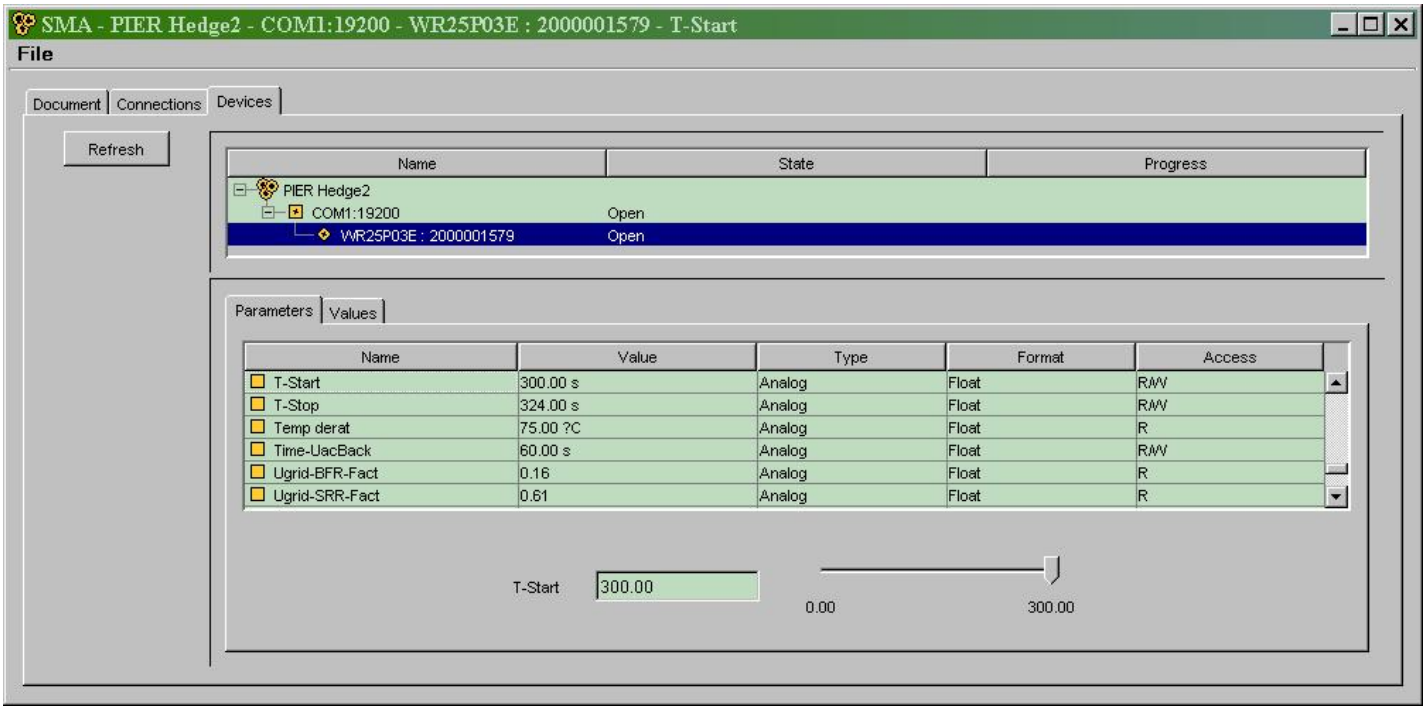
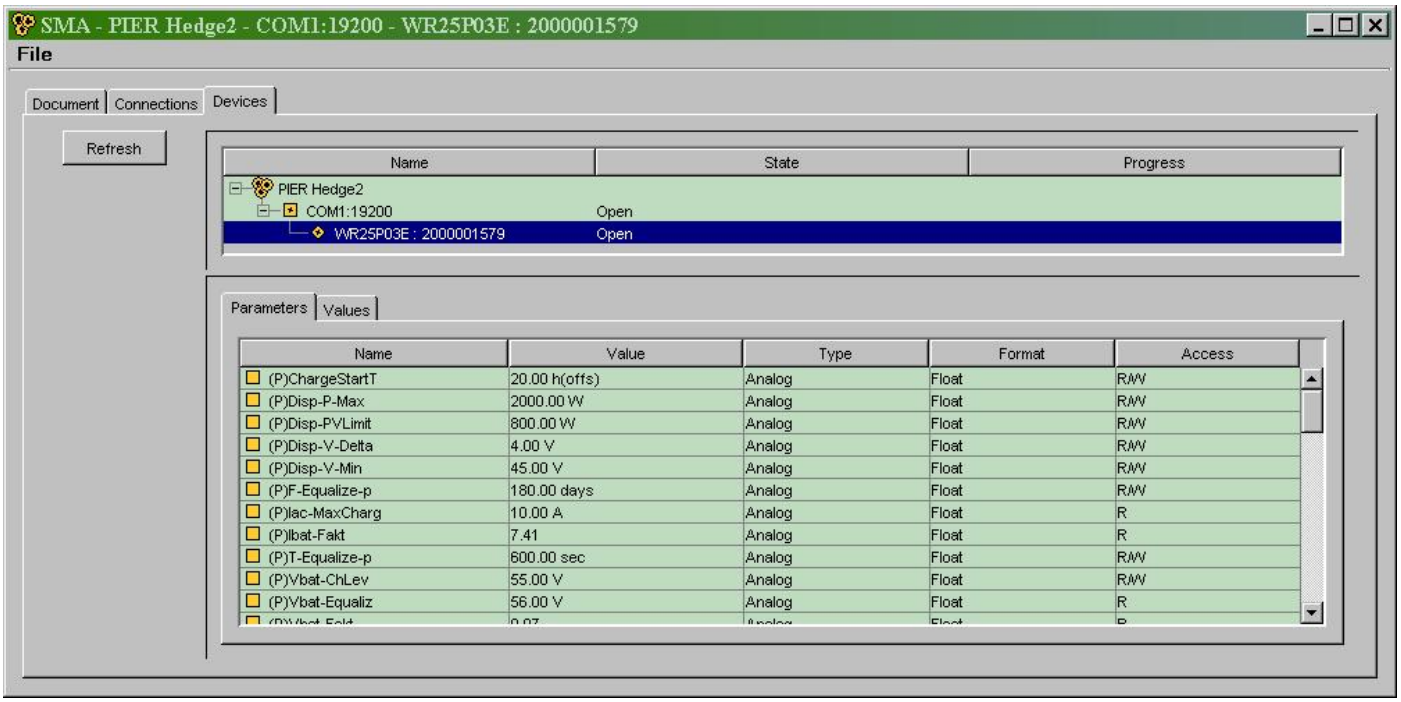


Table 2.5 Changing operating parameters from a PC



The result was a very simple and straightforward program that combined all control functions into a minimum number of interface screens. The program was designed to have a modular framework that could be easily modified for custom requirements if necessary.

2.8 Wireless Hardware for Remote Dispatch Function Control

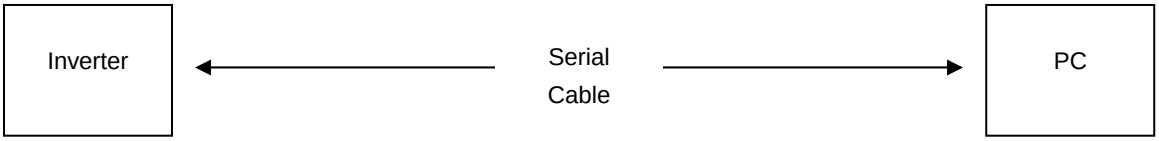
The requirement for wireless control of the inverter was not defined in the original Statement of Work. It was originally envisioned that some form of cellular technology would be incorporated into the inverter design. The belief was that a utility company could command all inverters installed within its service territory to begin dispatching power to the grid. Cellular technologies are more suited to addressing a single installed unit, rather than an entire fleet. Other forms of radio communication were considered. Some utility companies had already developed systems for load shedding during demand/capacity periods. One program reduces residential power rates if the customer allows a load shed relay to be installed on their air conditioning systems. These typically involved an addressable radio frequency receiver and power relay. When the utility company decides to disable a group of air conditioners, a radio signal is sent out to individual load shed devices. These devices disconnect the air conditioners within the targeted residences until the peak utility demands have subsided.

SMA considered using this technology; unfortunately SMUD had a proprietary design for the receiver/load-shed relay used within its service territory. Similarly, so did PG&E and SDG&E.

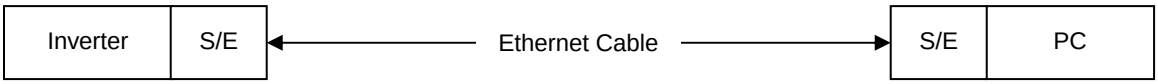
Since the concept of wireless control was more important than the actual technology used, the authors decided to use simple off-the-shelf wireless serial transmitters and receivers. The wireless hardware is effectively a replacement for existing serial communication hardware with a wireless medium. It incorporates off the shelf products to convert RS232/RS485 cabling to Ethernet cabling, which enables the use of 802.11b Wireless Ethernet. No changes are required to the existing software protocols, so backward compatibility with existing inverters and PC software is maintained.

The use of off-the-shelf hardware proves the concept of wireless control ability. Any technology could be inserted in place of the 802.11b Wireless Ethernet. This could be FM-RF, cellular, 900MHz wireless device, or any other wireless technology depending on the requirements of the broadcast region and the controlling party.

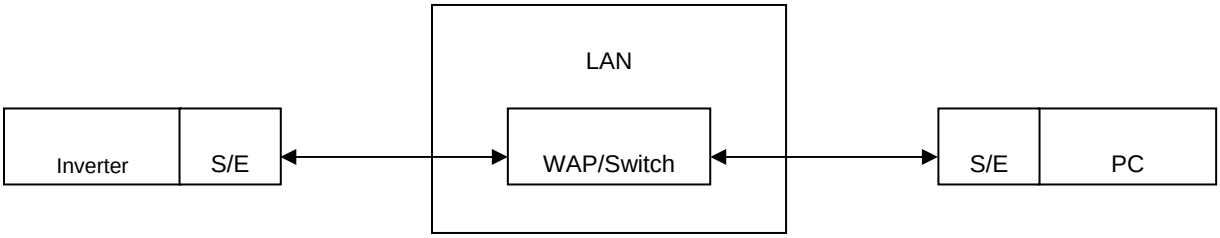
Conceptually the transformation from serial to wireless occurs in three steps, starting with the existing serial cable installation, depicted in the figure below.



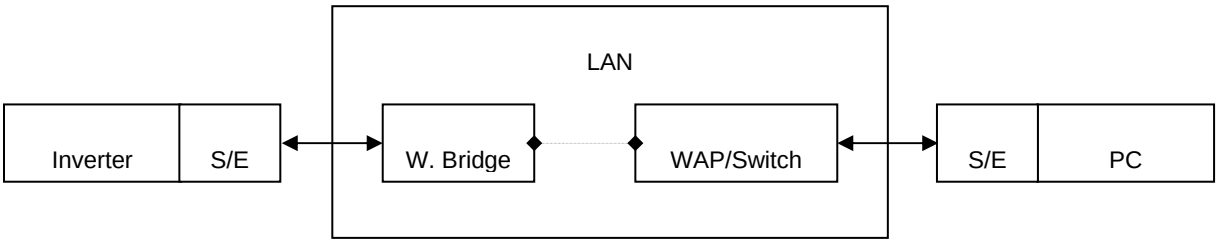
Step one is to convert from a Serial cable to an Ethernet cable. This is achieved using two Serial to Ethernet converters (S/E) at either end of an Ethernet crossover cable, depicted below. This is a valid configuration, which extends the maximum cable run length from serial limits (20-200 ft.) to Ethernet limits (500 to 1,000 feet)



Step two is to convert from an Ethernet crossover cable to two normal Ethernet cables, each connected to the Wireless Access Point/Switch (WAP/Switch). The WAP/Switch creates a Local Area Network (LAN). In this configuration the wireless function of the WAP/Switch is not used. This is a valid configuration and is depicted below. With no additional hardware within the LAN, the maximum connection distance doubles (1,000 to 2,000 feet) since there are now two cables. With additional hardware (routers/switches/bridges) added, the LAN could span the globe via the Internet, with unlimited connection distance.



Step three introduces a Wireless segment to the LAN, by adding a Wireless Bridge and activating the wireless function of the WAP/Switch. This configuration is depicted below. The newly created wireless segment has its own maximum connection distance. Assuming this requirement is satisfied, the LAN still potentially provides unlimited overall connection distance.



This was the configuration used to satisfy the wireless requirement of the PIER contract. The exact hardware used is detailed in the Appendices section of this report.

2.9 Integrated Field Testing of the Inverter and Dispatch Function

The final task of PIER project was complete system testing of the entire system. This was primarily done by verifying each of the Dispatch Function commands and parameter configurations worked in accordance with the State Machine specified in the original technical specification. A detailed test procedure was drafted to verify the inverter system operated per the specification.

The first test report was arranged in the following general test sections:

- **Physical construction inspection:** Identified any areas that were not compliant with UL1741 or good manufacturing practices.
- **General functional performance:** Verified general control functions such as voltage and frequency regulation.
- **Pre-power tests:** Confirmed physical wiring continuity between terminal blocks and key components. Also confirmed proper chassis and neutral grounding between the PV, battery and utility terminals.
- **Transition Tests:** This is by far the bulk of the test procedure. In this section, every state transition and sub-state transition was tested. Where applicable, operating parameters interrelations with the state machine were confirmed to function properly.

The second test report verified the PC interface, wireless communication link and dispatch functions performed in accordance with the technical specification. This primarily verified the state transitions and parameter interactions functioned as expected in the field test system.

The inverter performed as expected and in accordance with the technical specifications developed at the beginning of the project. A few minor construction issues were identified that would need to be corrected prior to UL listing and general product manufacturing.

3.0 Project Outcomes

3.1 Overall Accomplishments

The original primary objectives of this PIER project involved:

1. Developing a low cost grid-feeding inverter incorporating both the maximum power point tracking functions and backup power capabilities
2. Developing remote dispatch capability for renewable power systems.

Primary Objective 1 was clearly realized in the final construction of the inverter. The end design was a successful integration of a standard grid-tied PV inverter with the additional features of a battery back-up inverter in one package.

Primary Objective 2 was realized in concept. The inverter contained the ability to dispatch power to the grid from the battery from a remote location. The feasibility of doing so became questionable as the project evolved.

3.2 Technical Accomplishments

SMA America met all of the technical objectives of the inverter project, including:

Technical Accomplishment 1: Develop a single-stage bridge topology capable of battery charging from the grid, PV MPPT to the grid, and dispatching power from the battery to the grid.

The design topology for the inverter was specifically chosen to meet the requirements of this contract, as well as the market requirements for a multi-function PV and battery back-up inverter. The inverter has only one H-bridge type of conversion stage to convert either PV or battery DC power to AC. Only one source can be converted at a time. Most of the time the inverter would be converting PV power to the grid. During a grid outage, the inverter would not MPP track the PV array, since the bridge would be used to support local loads from the battery. In this case, the PV array would be tied directly to the battery, contributing some of the available PV power to the battery. The major operating modes of the inverter are grid-tied PV MPPT mode, battery charging from the grid, or dispatching power from the battery to the grid.

Technical Accomplishment 2: Demonstrate the feasibility of dispatchable power from distributed storage sources.

One of the primary states of operation developed for the inverter was Dispatch mode. To date the inverter is the only inverter with the capability to dispatch power from a storage battery with no renewable energy source feeding the battery. The feasibility of doing this is determined by many factors outside the consideration of this PIER contract. The reasons to dispatch power from a battery are different for the equipment owner and the utility company.

From the equipment owner's perspective, it only makes sense to deliver battery power to the grid if the equipment owner is being compensated for more than the power is worth. There are many ways to determine the value of stored power. There are many different rate schedules available, some being fixed rate, others varying by time-of-day usage, with many having surcharges for peak, surge, or VAR demand.

For example: The prevailing residential rate from the utility company is 12 cents per kWh. Considering the losses associated with charging and discharging batteries; some research indicates the round-trip losses can be as high as 50% of the source energy. This means that 30 kWh will be required to charge and discharge the battery for every 15 kWh of energy delivered to the grid. This results in the cost of energy being 24 cents per kWh. Add to this cost of battery wear-and-tear, maintenance, equipment amortization costs, etc, the utility company would have to pay 30 to 40 cents per kWh for the equipment owner to break even. It is unlikely that a utility company would be willing to pay the equipment owner's total cost for power since the current cost to produce power is as low as 4 cents per kWh in California. However, if the utility company is paying a high rate for power during peak capacity times, it may be less expensive to pay the inverter owners round-trip costs, rather than purchase power from a higher rate source or from a power broker. This example also shows why it is also not practical for the equipment owner to profit from buying power during off-peak hours and selling it back during peak times.

The equipment owner may also consider the value of power as the cost of generating power from a generator after the grid has failed. Depending on the cost of fuel, generator maintenance, wear-and-tear, round-trip efficiencies, etc., the resultant cost may be much higher than the cost of power from the inverter.

Another consideration is the time of day/year that the utility would be allowed to demand dispatch power from the inverter. Also, how much of the battery capacity the utility company could use before the equipment owner stopped the dispatch function.

These are just some of the foreseeable contractual issues that would need to be addressed between each utility company and equipment owner. Since these considerations are outside the scope of this PIER contract, simple provisions for dispatch control were integrated into the inverter design. The basic concept of delivering power from a battery to a utility is available and fully functional within this inverter.

Technical Accomplishment 3: Develop a method for remotely controlling the inverter to dispatch power to the grid.

A simple method for controlling the inverter from a remote location was developed externally from the physical inverter. It incorporates off-the-shelf products to convert RS232/RS485 cabling to Ethernet cabling, which enables the use of 802.11b Wireless Ethernet transmitters. The requirement for wireless control of the inverter was never defined in the original Statement of Work. It was originally envisioned that some form of cellular technology would be incorporated into the inverter design. The belief was a utility

company could command all inverters installed within its service territory to begin dispatching power to the grid. Cellular technologies are more suited to addressing a single installed unit, rather than an entire fleet. Other forms of radio communication were considered.

Since the concept of wireless control was more important than the actual technology used, the authors decided to use simple off-the-shelf wireless serial transmitters and receivers. The wireless hardware is effectively a replacement for existing serial communication hardware with a wireless medium. No changes are required to the existing software protocols, so backward compatibility with existing Inverters and PC Software is maintained.

Technical Accomplishment 4: Increase the overall inverter efficiency compared to existing grid-tied battery based inverters to the levels found in dedicated PV grid-tied inverters. Baseline systems will be instrumented and compared to measured results from the final product testing.

The baseline study of the SW-GTI 5548 battery back-up and PV grid-tied inverter showed instantaneous efficiencies of 69% and overall energy capture efficiencies of 55%. These low efficiency values are the result of an inaccurate power tracker, poor DC current regulator, two-stage conversion topology, and continuously float charging the battery. The nighttime losses associated with float charging the batteries consumed over 50% of the PV power exported to the utility during the day.

The inverter instantaneous and overall efficiencies were found to be almost identical at 92%. The inverter performs as a simple grid-tied PV inverter unless the battery requires charging. Well maintained batteries will require recharging due to leakage approximately once per month for a small number of hours. The amount of energy necessary to recharge the batteries compared to the PV energy generated throughout the month turns out to have little effect on the overall efficiency result.

3.3 Financial Accomplishments

SMA met the financial objectives of this project.

Financial Accomplishment 1: Reduce the specific cost of the inverter package to a level similar to that found in grid-tied PV inverters.

Combining all the functional elements of a back-up power and a grid-tied system into one device reduced the overall system cost by approximately 30% compared to similar systems that integrate multiple single-function devices.

Since this inverter only operates as either a grid-tied PV inverter or a battery back-up inverter, the same hardware is used for both operating modes. Combining the PV and battery functions into a single-bridge topology reduces the number of inverters normally needed for both of these functions to just one inverter. Historically, a special inverter was

needed to manage the battery state-of-charge and support of the local loads when the grid failed. And a separate inverter was needed to manage the PV power to the grid, or to the batteries, depending upon the system design. Integrating both functions into one inverter increased the complexity of the inverter, but reduced overall inverter components by approximately 40%. Some additional parts are necessary for interconnection of the PV system and battery into the inverter. But the overall parts increase is approximately 10% compared to a typical stand-alone battery inverter. Major components (such as the enclosure, transformer, filter inductors, bridge capacitors, circuit boards, etc.) were reduced by half when compared to a separate grid-tied battery inverter and an additional back-up inverter.

Financial Accomplishment 2: Reduce overall system costs by reducing the balance-of-system components compared to existing back-up power systems.

The total major component count was reduced from two inverters to one inverter, while reducing required accessories (switches, breakers, terminal blocks, wiring, etc.) which were integrated into this inverter.

The overall system costs were reduced by approximately 50%. Only one set of AC interconnection components (switches, breakers, conduit, and wire) are necessary since there is only one inverter. DC wiring is also reduced by running both the battery and PV source wires into one inverter. On the DC side, overcurrent protection devices are included within the inverter, negating the need to install these devices between the power sources and the inverter.

Financial Accomplishment 3: Simplify installation of a multi-mode power system, further reducing overall system cost.

Since there are fewer components to install, labor costs are significantly reduced. Labor is the second highest cost of any PV system, second to the cost of the PV panels. Simplifying system installation has a dramatic effect on the overall system cost. The combination of two inverters into one inverter package along with the reduction of the balance-of-system components discussed above significantly reduces the amount of labor necessary for this inverter compared to other typical systems. Labor costs for the inverter are reduced by approximately 25% when considering just the labor for installing the inverter(s) and balance-of-system components.

3.3.1 SMA Cost Share

The original budget for the PIER project included forecasts for cost sharing from both SMA and SMUD. Both organizations were each expected to contribute $60,000 to assist the development of the inverter. SMA's contribution was budgeted in a task for submitting the inverter to Underwriters Laboratories (UL) for evaluation to UL1741. SMUD's contribution was originally planned to cover the expense of PV modules for final testing of the inverter in a real-world installation.

During the project, it became clear that the inverter would not be a product that was directly ready for the United States market. However, technology developed for the inverter could certainly be used in other SMA products for the United States markets. It was determined not to approach UL with the inverter. SMA foresaw from the beginning of the project that the PIER project costs would far exceed the amount in the original budget. SMA invoices submitted to SMUD detailed cost share amounts over $298,000, from multiple tasks, to develop the inverter.

SMUD's cost share had to be shifted from the original plan of supplying PV panels to the final test. Field testing the inverter was found to be more complicated than originally planned. Due to liability concerns, SMUD's legal counsel determined that the inverter could not be installed at a private residence or commercial location because it did not have a UL certification. Since it was not practical to obtain a UL certification before field testing had been performed, we were forced to look for another test location. The only location allowable for testing was at SMUD's Hedge Substation, "behind the fence." This site proved to be acceptable, although it was very close to the utility source and had few local loads present. The site was included an equipment shed with modules on the roof that were from a Powerlight PIER project. Field testing of the inverter was performed at this location.

3.4 General Outcomes

The funding of the Maximum Power Point Tracker Inverter for PV Systems with Energy Storage and Dispatchability PIER project by the California Energy Commission has allowed SMA America to develop the technology necessary to incorporate the function of two different inverter functions into a single inverter. It has also allowed SMA America to develop the ability to dispatch stored energy to the grid. This technology is easily adaptable to other products being developed by SMA America. During the development of the inverter, SMA was also developing the Sunny Island 4248U (SI4248U) battery back-up inverter. This product utilized the basic control boards found in this inverter. Many of the firmware modules used to control this inverter was also ported into the SI4248U. This product was released in June 2004.

SMA America is planning to further enhance the Sunny Island product in two future designs. The second design of the SI4248U will incorporate advanced battery management and grid-feeding functions. The grid-feeding will primarily be used for systems that use low-voltage ($48V_{DC}$) renewable energy sources and require feeding their power through the battery.

The third design will incorporate combining a low-voltage PV array into the DC input in the same manner as implemented in the new inverter. The third phase of the SI4248U will have the same functionality as the new inverter. The only difference being the description of the Dispatch Function. The equipment owner will control when to deliver power to the grid rather than the utility company. The internal method for doing this will be identical to

the new inverter. The SI4248U will be easily configurable for remote utility control if and when utility companies develop a standard for dispatching stored energy from privately owned distributed generation sources.

4.0 Conclusions and Recommendations

4.1 Applications of The Technology

Through the development of the PIER project, SMA has expanded its understanding of the stand-alone inverter. Before the PIER project, SMA had only the Sunny Island for Europe. This was a very complicated off-grid only inverter that had very few real-world applications. The inverter development created a simplified platform for off-grid inverters and helped to create simplified control algorithms.

Most importantly, the PIER project spearheaded our efforts to grid-tie a battery based inverter. The dispatch function is basically a control scheme that delivers power from batteries to the utility. The inverter also developed the ability to switch from grid-tied PV MPPT mode to off-grid battery backup mode in one product. These applications are frequently requested from owners of off-grid and grid-tied inverters.

4.2 Commercialization Potential

The functions discussed above helped to create the Sunny Island 4248U. This inverter was released in the United States in the first quarter of 2005. It contains the basic battery and stand-alone features developed for the inverter. Future phases of the Sunny Island inverter development plan to incorporate the MPPT and dispatch functions. At this time it is not known if the utility companies will be interested in controlling this power, but there are other applications for this technology. For instance, power from PV grid-tied inverters is delivered to the grid at the schedule of the sun's cycles. Time based rate fees from utilities make it advantageous to control the time when power is delivered to the utility. This is almost identical to the dispatch function developed for this inverter, with the control being shifted from the utility company to the equipment owner. This function will be integrated into future revisions of the Sunny Island inverter.

4.3 Recommendations

The following observations and suggestions are provided to improve the process for future PIER contracts:

4.3.1 Technical Considerations

The Dispatch Function was one of the main technical aspects of the PIER project. Unfortunately, how to implement this function was not considered. For future PIER projects, some detail should be considered at the onset of the project to help identify any technical or contractual issues that could impact a critical project task.

4.3.2 Field Testing Location

It was very difficult to find a test location since the inverter was not UL listed. SMA's field test period was drastically shortened. It took many months for SMUD's legal department to approve a test site, and then many more to prepare the site for the inverter. Having located an acceptable test site earlier in the project process would have improved the quality and duration of the field testing.

4.4 Benefits to California

This inverter is a crucial step to developing an advanced SMA back-up power system that incorporates grid-tied PV and allows exporting of stored power to the grid. From the development of this inverter, SMA has developed a basic back-up power system called the Sunny Island 4248U. This product was brought to market in the summer of 2004. Further developments are underway to integrate the dispatch function into the battery management system and also integrate PV into the system. These functions will be released over the next two to three years in advanced versions of the Sunny Island.

The authors see the market for back-up power systems increasing as energy prices continue to increase and grid reliability continues to decrease. Utility companies will continue to increase time-of-use and peak-support charges to their customers. The Sunny Island family of products will be well positioned in this energy market.

SMA is already seeing interest in a product that can dispatch power from stored energy sources to counter load peaks, either in short duration (starting of a large motor) or long duration (afternoon air-conditioning loads). Many utility customers are beginning to be billed for peak demand (energy surges caused by their loads). Future versions of the Sunny Island will monitor the building load demand and supplement utility power when peak loads and surge support is needed. This will level the utility demand and reduce excessive support charges.

Time-shifting of energy dispatch is also a common subject today. The market is beginning to request the ability to store energy as it is created, and then deliver it to the utility at a different time of day. For instance, wind power generated at night is stored in batteries until the peak of the next day. The inverter would then deliver the stored energy to the grid at peak time-of-use rates and realize a higher sell-back rate then they would have received when the energy was created. Future versions of Sunny Island will have the ability to deliver stored energy at preprogrammed days and times.

The PIER project has provided SMA the means to develop these advanced Sunny Island functions that will provide the California energy market with products it needs in the coming years.

Appendix A

Inverter Software Parameters

name	unit	min	max	default	level r/w	description
SMA-SN		0	4294900000	0	U/S	SMA serial number
Upv-Start	V	33	80	35	U/I	
T-Start	s	0	300	1	U/I	time that PV voltage must be present before starting grid feeding
T-Stop	s	1	18,000	1	U/I	
T-Ramp	s	0	300	0	U/U	
Release		0	255	0	U/U	
SetBit		0	7	0	U/U	
ClrBit		0	7	0	U/U	
Usoll-Konst	V	25	80	45	U/U	setpoint value (PV voltage) for Uconst operation
UInsel-Nom	V	0	255	115	U/U	setpoint value (output voltage) for Iconst operation
KP_Ureg		0	20	1,8	S/S	controller parameter
KI-Ureg		0	10	0,04	S/S	controller parameter
KD-Ureg		0	1	0	S/S	controller parameter
Pmax	W	0	5,000	2500	S/S	absolute max. power the device is able to deliver
Plimit	W	2500	2,500	2500	U/-	max. power the device should deliver
I-NiTest	mA	0	7,000	0	I/I	
Cnt-Imax		1	1,000	3	S/S	number of Imax errors
Upv-Max	V	15	80	75	S/S	max. seen PV voltage
Upv-Stop	V	0	80	20	S/S	stop MPP operation below this PV voltage
Uac-Min	V	90	109	100	I/I	min. allowed grid voltage for grid feeding
Uac-Max	V	110	135	125	I/I	max. allowed grid voltage for grid feeding

name	unit	min	max	default	level r/w	description
Fac-delta-	Hz	0	7.5	0.19	I/I	min. allowed tolerance of grid frequency
Fac-delta+	Hz	0	7.5	0.19	I/I	max. allowed tolerance of grid frequency
dFac-Max	Hz/s	0.01	4	0.25	U/I	max. allowed changing speed of grid frequency
THS-Derating	°C	70	90	80	S/S	THS temperature to start derating
Upv-Fakt		0	100	0.11874	S/S	calibration factor for PV voltage measurement
Iso-Fakt		0	0.01	0.004883	S/S	calibration factor for Riso measurement
It-Fakt		0	150	4.5	S/S	calibration factor for current measurement
Iac-Fakt		0.1	100	5.75	S/S	calibration factor for grid current measurement
Hardware-BFS	Version	0	100		U/-	hardware version
Software-BFR	Version	0	100		U/-	software version BFR
Software-SRR	Version	0	100		U/-	software version SRR
Uac-BFR-Fakt		0.149	0.165	0.154	S/S	calibration factor for grid voltage measurement (BFR)
Uac-SRR-Fakt		0.58	0.64	0.616	S/S	calibration factor for grid voltage measurement (SRR)
AD0-3KorrFakt		0	65,536	32768	S/S	A/D correction value
AD0-3KorrOffs		0	20,000	10000	S/S	A/D correction value
AD4-7KorrFakt		0	65,535	32768	S/S	A/D correction value
AD4-7KorrOffs		0	20,000	10000	S/S	A/D correction value
Inst.-Code		0	4294900000	0	I/I	installer code
E_Total	kWh	0	200,000	0	I/I	total energy fed into the grid
h_Total	h	0	200,000	0	I/I	total operating hours
Udc-Min	V	20	50	40	I/I	min. allowed inter-circuit voltage

name	unit	min	max	default	level r/w	description
Udc-Min-Hyst	V	0	20	5	I/I	amount that inter-circuit voltage must rise before restarting operation
U-Island-Min	V	10	250	80	I/I	min. allowed output voltage in island mode
Hyst-UacBack	%	1	20	1	I/I	
Time-UacBack	s	1	3,600	60	I/I	grid must be present for this time before switching from ISLAND back to MPP
Stat-msg Displ		0	5	0	I/I	
Comm-Time	s	0	6,500	60	S/S	
KP-Ireg		0.1	100	25	S/S	controller parameter
Tn-Ireg		10	10,000	365	S/S	controller parameter
KP-Ireg-Faktor		1	65,535	1576	S/S	controller parameter
KP-Ireg-Offset		0	65,535	0	S/S	controller parameter
(P)Ubat-Fakt		0.01	100	7.13	S/S	calibration factor for battery voltage measurement
(P)Ibat-Fakt		0,01	100	7.32	S/S	calibration factor for battery current measurement
(P)UAC-Nominal	V	90	135	120	S/S	nominal voltage of output voltage in island mode
(P)IAC-MaxCharg	A	0	16	8	S/S	max. battery charge current
(P)IAC-Complete	A	0	32	20	S/S	total inverter output current
(P)FAC-Nominal	Hz	50	70	60	S/S	nominal frequency
(P)UBAT-Min	V	35	48	38	S/S	min. battery voltage, stop all actions
(P)UBAT-Equaliz	V	48	68	58	S/S	max. battery voltage for cell leveling
(P)UAC-MaxDerat	V	80	120	108	S/S	min. output voltage in case of derating in island mode

name	unit	min	max	default	level r/w	description
(P)PV-PowerLim	W	1000	2,500	2000	I/I	PV power limit for staying in MPP mode when DISPATCH is requested
(P)Dispatch-Lev	V	20	50	43	I/I	below this battery voltage DISPATCH is not allowed
(P)Disp:RestLev	V	1	10	1.5	I/I	amount that battery voltage can rise without entering DISPATCH
(P)PBAT-max	W	500	2,500	2500	I/I	max. power that can be feeded from battery into the grid
(P)T-Pv<DF_MPPT	s	1	100	10	I/I	after PV power drops below DF_MPPTOVERRIDE wait this time before switching from MPP to DISPATCH
(P)UBAT-ChLev	V	40	70	56	I/I	battery charging voltage
(P)UBAT-ReChLev	V	40	70	46	I/I	recharge battery when voltage reaches this level
(P)T-Equalize-p	s	1000	5,000	3600	I/I	battery equalize duration
(P)F-Equalize-p	days	1	500	30	I/I	battery equalize is entered after the specified number of days
(P)ChargeStartT	h	0	25	15	I/I	start time for battery charging
(P)THS-MaxTmp	°C	90	110	100	I/I	THS max. temperature, stop all action
(P)THS-MaxOn	°C	60	100	90	I/I	THS temperature to reactivate operation
(P)THS-CoolStar	°C	50	100	80	I/I	THS temperature to start cooling fan
(P)THS-CoolEnd	°C	40	70	60	I/I	THS temperature to stop cooling fan
(P)THS-CoolFull	°C	60	130	95	I/I	THS temperature to start max. cooling
(P)TTF-Derating	°C	70	110	100	I/I	TTF temperature to start derating
(P)TTF-MaxTemp	°C	90	130	100	I/I	TTF max. temperature, stop all action

name	unit	min	max	default	level r/w	description
(P)TTF-MaxOn	°C	60	110	80	I/I	TTF temperature to reactivate operation
(P)TTF-CoolStar	°C	50	100	80	I/I	TTF temperature to start cooling fan
(P)TTF-CoolEnd	°C	40	100	70	I/I	TTF temperature to stop cooling fan
(P)TTF-CoolFull	°C	60	130	100	I/I	TTF temperature to start max. cooling

Below is a list of the hardware used to accomplish wireless communication and control of the inverter from a remote PC:

Two Serial to Ethernet converters:

Moxa Technologies, NPort Express DE-311, serial to LAN device server

One 802.11b Wireless Access Point:

Linksys Group Inc, BEFW11S4, Wireless Access Point with 4 Port Switch

One 802.11b Wireless Bridge:

Linksys Group Inc, WET11, Ethernet Bridge.