August 2000 • SR-520-28820

Subcontractor Report

PVMaT – OMNION Series 3300: Photovoltaic Power Conversion System for Utility Interconnected Application

Annual Report
May 1997- February 1999

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Prepared under Subcontract No. ZAF-5-14271-02

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PREFACE

This Annual Report describes the technical progress made under the DOE/NREL subcontract #ZAF-5-14271-02, PVMaT Phase 4A - Product Driven Manufacturing from October 1st, 1995 through October 17th, 1998. The work performed was geared towards making advancements in three major areas of three-phase, utility interconnected and photovoltaic power conversion. The three major areas consisted of cost, reliability and performance.

The following OMNION personnel have contributed to the efforts covered in this report:

David Porter	Hans Meyer	William Leang	Robert Massey
Peter Keck	Jeff Vohar	Dale Stefanac	Randy Koker
Deanna Tracy	Mark Haug	Roger Troyer	Tron Melzl
Pete Armstrong	Dan Zietlow		

Support was also received from Wayne Hunnicutt, Mechanical Engineer.

EXECUTIVE SUMMARY

Background [1]

The Photovoltaic Manufacturing Technology (PVMaT) Project is a research and development (R&D) partnership between the U.S. federal government (through the U.S. Department of Energy - National Renewable Energy Laboratory) and members of the U.S. photovoltaic industry. It began in 1990 to help the U.S. photovoltaic (PV) industry extend its world leadership role in manufacturing and developing commercial PV modules and systems. The project is designed to help the industry improve manufacturing processes, accelerate manufacturing cost reductions for PV modules, improve commercial product performance, and lay the groundwork for substantially scaling up the capacity of U.S.-based PV manufacturing plants.

As part of PVMaT Phase 4A - Product Driven Manufacturing, OMNION Power Engineering Corporation was awarded a contract to develop a Three-Phase Power Conversion System for Utility Interconnected Photovoltaic Applications.

Objectives

The objectives of this contract are to make advancements in three major areas of three phase utility interconnected photovoltaic power conversion: cost, manufacturability, reliability, and performance. OMNION has established the following goals for meeting these objectives:

- **Cost:** The total manufacturing cost of a nominal 100-kW power conversion system (PCS) will be reduced from approximately $0.50/watt to $0.25/watt when built in production lots of 100 units.
- **Reliability:** A design goal of 40,000 hours mean time between failure (MTBF) has been established for the new Series 3300 Photovoltaic Power Conversion System.
- **Performance:** Design goals have been established to (1) improve converter efficiency from 95.5% to 96.5%, (2) meet FCC regulations for electromagnetic interference, and (3) reduce audible noise to below 60 decibels.

Approach

Omnion developed comprehensive product specifications for a 100-kW inverter by surveying customers, industry experts and end users of photovoltaic power inverters. This survey process was used to define standard and optional features of the inverter. In Phase I, the first Series 3400 prototype inverter was built using soft-switching technology. During the soft-switching technology development and prototype testing, specific hardware barriers were found. The first barrier was the active clamp power device failure rate. The second barrier was the lack of a working input boost circuit. These two barriers prevented the development of an operational 100-kW soft-switching inverter.

During Phase II after an extensive development effort to resolve these two barriers, OMNION decided to change the switch technology platform to hard-switching technology. OMNION discussed this change with the Technical Monitoring Team and received approval on March 10, 1998 to proceed with the proposed hard-switching solution for the 100-kW three phase utility interconnected photovoltaic converter deemed the Series 3300. During Phase II, OMNION final-

1. Text From NREL Web Site 10/19/98 *URL http://www.nrel.gov/ncpv/pvmat.html*

ized the revised and repackaged design for the prototype 100-kW photovoltaic power conversion system. OMNION also conducted tests on modified manufacturing equipment and conducted a pre-production run of the prototype 100-kW photovoltaic power conversion system. Specifications for the Series 3300 PCS (see appendix D) were completed in March 1997 and transmitted to TMT on April 20, 1998.

Phase III of the contract was geared toward the development of a production version of the new Series 3300 hard-switching inverter. The end goal of Phase III is to have an UL listed production unit of the Series 3300 PV inverter. To reach this goal, a Semikron Skiip bridge (**S**emi**K**ron **i**ntergrated **i**ntellegent **P**ower) was selected for the power train which is controlled by an Omnion inverter control board set. The overall inverter cost was significantly reduced by the Skiip bridge power train.

In Phase III, decisions to determine the finalization of the Series 3300 packaging were driven by cost, the features and options survey and UL listing requirements.

The Series 3300 is presently in production and in the process of obtaining UL listing approval.

Summary of Results

Phase I - Development of a Prototype PCS:

A key step in developing the Series 3400 inverter was the completion of the control boards test fixture. This allowed OMNION to simultaneously develop software and to test the inverter control hardware. OMNION continued to work with SST on the development of the control of the core resonate module and the boost converter. OMNION also conducted extensive testing in attempt to solve problems associated with the boost converter.

The completion of the prototype software and the prototype PCS allowed OMNION to proceed with power testing of the prototype PCS. The power testing achieved a 75-kW output level, However, hardware problems with the active clamp device and the boost circuit prevented operation at the 100-kW level. The Series 3400 inverter was demonstrated at 75-kW to a group of potential customers, end users and PV industry representatives. Along with the demonstration, the product specifications were also reviewed. The comments made regarding the product specifications were incorporated into the final prototype specifications. By the end of Phase I, the failure modes and effects analysis were completed on the Series 3400 design. The boost circuit was identified as a critical component that needed to be re-designed by SST. These re-design efforts were initiated in Phase I. In conclusion to Phase I, a review meeting was held with the Technical Monitoring Team.

Some of the major accomplishments achieved in Phase I included:

- The development of a completed prototype software
- A completed assembly of the prototype power conversion system

Phase II - Finalization of Series 3400 Prototype PCS and Manufacturing Process Design:

Phase II focused on OMNION's effort to develop the final prototype packaging for the Series 3400 inverter and the manufacturing process design for the Series 3400 production model. OMNION also continued to work with SST on the development of a working boost circuit and a reliable clamp device. OMNION initiated the final production unit package design for the Series 3400 soft-switching 100-kW power conversion system and completed a draft copy of an operation and maintenance manual.

Also as a part of Phase II, OMNION completed the design and fabrication of a DC power supply (500A, 600VDC) which was used to test the Series 3400 inverter. The 500A DC power supplies proved to offer a greater control over the DC input to the prototype Series 3400 inverter. The design of test and manufacturing fixtures were initiated as part of the manufacturing process design. Testing of the re-designed boost converter was conducted at OMNION, However, the re-design efforts by SST did not overcome the problems with the boost converter or the active clamp device. OMNION conducted an internal evaluation of the prototype Series 3400 power conversion system to determine solutions for the problems experienced from active clamp device failure, severe power level deratings at slightly elevated ambient operating temperatures and SST's inability to deliver a working boost converter section. A proposal to make a transition to a hard-switching inverter was submitted to the PVMat Technical Monitoring Team (TMT). The proposal submitted detailed how the hard-switching solution would meet a majority of the initial project goals. The proposal for the transition was approved by the TMT on March 10, 1999.

Some of the major accomplishments in Phase II included:

- A complete DC power supply for production testing
- Completion of the factory testing for the prototype soft-switching 100-kW power conversion system.

Phase III - Finalize Pilot Production for 3300 PCS and Manufacturing Process Design:

OMNION had already begun the research and design work for a hard-switch inverter prior to the TMT approval on March 10, 1999 by reviewing several different power bridge packaging concepts. OMNION selected the Semikron Skiip bridge as the core of the new hard-switched Series 3300 inverter design. The Skiip bridge allowed for rapid development of the Series 3300 prototype inverter packaging.

The Design Phase process developed as part of the Sandia Quality contract #AU-5808 was used to coordinate the development and documentation of the Series 3300 inverter. Assembly of the Series 3300 prototype was digitally photographed which allowed the development of a Series 3300 manufacturing manual.

The Series 3300 prototype successfully passed OMNION's development and factory testing procedures and first Series 3300 prototype was delivered to Sandia National Laboratories for independent testing.

Packaging improvements were incorporated in the Series 3300 pilot production inverter from the manufacturing review of the first Series 3300 prototype. The Series 3300 manufacturing manual was completed for the Series 3300 inverter. The O&M manual includes details on installation, equipment clearances and diagnostic messages. A pilot production Series 3300 inverter is currently in the UL listing approval process. Some major accomplishment made in Phase III include:

- Completion of factory testing of the new Series 3300 hard-switching 100-kW prototype power conversion system
- A completed O&M manual for the new Series 3300 hard-switching 100-kW prototype power conversion system

Technology for a three phase, utility interconnected, photovoltaic inverter originated with the Series 3200 which progressed to the of the Series 3400 which then progressed to the present Series 3300 system. The benefits of these developments are explained below:

Development Benefits Summary PCS Series 3300 vs. 3200
A) Elimination of Non-essential Features: The 3300 has been developed with customer/user inputs so that only essential features are included. In the 3200, there could be up to 24 Printed Circuit Boards (PCB's) in each inverter. The 3300 has 3 PCB's in the Skiip bridge and 6 PCB's in the rest of the inverter for a total of 9 printed circuit boards.
B) Point Design vs. Flexibility: A highly integrated board set used in the 3300 to provides flexibility in system configuration while still reducing the board count to half of the 3200.
C) Next Generation Control- More Highly Integrated: See above two points.
D) Reduced Magnetics: For the same specifications, a 3200 required 9 single phase reactors at $750 each. The 3300 requires one reactor at about $1300, reducing the cost of Magnetics from $6750. The cost of the new inductors are 20% of the cost of the old inductors.
E) Reduced Manufacturing Labor: Since the 3300 uses the completely assembled and tested power bridge from Semikron, 20 hours of power bridge assembly time that is needed for the 3200 can be eliminated. The reduction in complexity allows a further savings of about 100 hours. In addition, since the 3300 is a standard unit, the cabinet and wiring are done the same way each time resulting in another 100-hour reduction of hours. Overall, the labor hours should be about half of the labor hours in a 100-kW 3200.
F) Reduced Size/Weight-Lower Shipping Cost, Ease of Installation: A 100-kW 3200 was housed in a 76" X 60" X 40" enclosure. The 3300 is housed in a 72" X 60" X 18" cabinet for a volume reduction to 43% of the 3200 size and a weight reduction to about 60% of the 3300. The reductions in size and weight lead to lower shipping cost and result in easier installation.
G) Reduced Assembly Labor: As discussed in E) above, the assembly labor is about half of the labor required for a 3200.
H) Reduced Test Labor: With the reduction in PCB's, the time to test boards is cut in half. In addition, the time required to test the entire system is cut in half. This amounts to a reduction of about 20 hours on PCB's and about 20 hours on system tests.

Development Benefits Summary PCS Series 3300 vs. 3200
I) Reduced Parts Count: This is discussed in A) above with the reduction of PCB's, and in D) with the reduction of magnetics. In addition, the number of bridges (IGBT's, Heat sinks, ...) was reduced from 3 to 1.
J) Reduced Complexity: As the parts count went down, the complexity of the system went down. See the discussion in I) above.
K) Ease of service: With the reduction in complexity in J) above, the ability to service the system increases. This is due to the need for fewer spare parts, and the ease with which the problem can be found.
L) Better Thermal Design: On the 3200, three bridges were required to get 100-kW. Now only one bridge is required. The maximum power rating on the 3200 was thermally limited; the 3300 power rating is also thermally limited.
M) Improved Efficiency: The 3300 should be slightly higher (0.1%) than the 3200 only because the control power will be reduced. The two systems are comparable.
N) Reduced EMI: An EMI filter included with the 3300 brings it into compliance with FCC part 15 regulations. This was not done for the 3200, so the 3200 did not comply with FCC part 15 regulations. Without the filter, the generated EMI will be the same for both designs.
O) Reduced Audible Noise: Inverter noise comes primarily from the inductors and the blowers. In the 3200 the predominant noise is from the inductors. On the 3300 the predominant noise is the blowers. This is due to the use of air core toroid inductors. Most noise on an inductor comes from the core, and tape wound C cores like those used on the 3200 inductors are very noisy. The air used as a core on the 3300 is very quiet.

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Section 1: Project Overview

Project Overview

OMNION Three-Phase Power Conversion System for Utility Interconnected Photovoltaic Applications Project

As part of PVMaT Phase 4A - Product Driven Manufacturing, OMNION Power Engineering Corporation was awarded a contract to develop a three-phase power conversion system for utility interconnected photovoltaic applications. In Phase I, OMNION developed a prototype 100-kW, three-phase, photovoltaic power conversion system. In Phase II, OMNION finalized the revised and repackaged design of the prototype power conversion system and in Phase III, OMNION changed switching technology from 3400 soft-switching to 3300 hard-switching technology with a final goal of a completing a UL listed pilot production unit.

Approach Used

The design methodology and approach followed for the prototype 100-kW Photovoltaic Power Conversion System (PCS) development entailed a two-phase effort for (1) the development of a prototype photovoltaic power conversion system and (2) the finalization of a revised and repackaged design. The approach for meeting the project's objectives included:

Phase I - OMNION developed comprehensive product specifications with input from a customer/user group. The draft product specifications were prepared based on OMNION's understanding of customer preferences and current technological trends. OMNION designed and built a prototype 100-kW, three-phase power conversion system in conjunction with Soft Switching Technologies Corporation (SST) which incorporated a soft- switching resonant DC link converter. The PCS was demonstrated at 75-kW (without the boost circuit) and the product specifications were reviewed with the customer/user group.

Phase II - OMNION finalized the revised and repackaged design for the soft-switching 100-kW power conversion system product (OMNION Series 3400). OMNION also conduct tests on modified manufacturing equipment and conducted a pre-production run of the prototype 100-kW power conversion system.

During Phase II factory testing of the prototype 100-kW soft-switching PCS, problems with the soft-switching caused OMNION to re-evaluate the use of soft-switching technology and to recommend the transition from soft-switching to hard-switching technology.

With the approval from the Technical Monitoring Team (TMT), OMNION prepared new product specifications to incorporate the new hard-switching into the new Series 3300 100-kW prototype PCS product design.

Phase III - The objective of Phase III of the subcontract was to implement design modifications from the prototype Series 3300 PCS into the pilot production and pre-production versions of this product, then to complete the UL testing required to gain that listing. OMNION designed and built a new prototype system package. OMNION factory tested the new hard-switching 100-kW prototype Series 3300 PCS. . OMNION finalized the revised and repackaged design for the new hard-switching 100-kW Series 3300 PCS and prepared an O&M Manual for the new hard-switching 100-kW prototype PCS. OMNION also conducted tests on modified manufacturing equipment and conducted a pre-production run of the new prototype 100-kW power conversion system.

Upon completion Phase III, OMNION's goal is to have a complete production-model power conversion system (PCS) with UL listing approval.

Accomplishments Overview

The goals of the PVMaT project are to improve photovoltaic (PV) manufacturing processes and products, accelerate PV manufacturing cost reduction and lay the foundation for significantly increased production capacity, thus assisting the U.S. industry in retaining and enhancing its world leadership role in the commercial development and manufacture of PV systems.[2]

Under this effort, OMNION also worked toward PVMaT goals of developing quality assurance, environmental safety and health programs. In keeping with these objectives, OMNION:

1. Improved its power conversion system manufacturing processes. This was accomplished by facilitating the flow of materials and components to the assembly line, incorporating jigs and fixtures to ease product handling and implementing semi-automated product testing. The concept of using cellular manufacturing will be investigated and adopted where appropriate. These improvements address reliability, efficiency, electromagnetic interference and audible noise.
2. Reduce manufacturing cost. This will be accomplished by refining product specifications in conjunction with its customers,

designing a standard “point design” product, and careful packaging engineering. The use of standard components from our suppliers reduced the custom engineering cost component of the product. The manufacturing review instituted as part of the design phases process has helped to identify and reduce manufacturing costs.

3. Lay the groundwork for increased production. This will be accomplished by minimizing production labor content, automating test functions, and instituting manufacturing processes to minimize material handling. The manufacturing process was documented to standardize the assembly procedure. The manufacturing documentation will be used for training new personnel when the production levels increase.

2. Text From DOE/NREL PVMaT RFQ #RAF-4-14271 Enclosure III - Work Statement 7/13/94

Section 2: Project Results

Three-Phase Power Conversion System for Utility Interconnected Photovoltaic Applications

Phase I

Specification Development, Prototype Design and Fabrication

The emphasis of efforts in the Phase I tasks was to focus on the review process with the customers/users group. This valuable input was the main driving force in finalizing the specifications for the Series 3400 pre-production model to be procured under Phase II.

Task 1- Specification Development

The goal of this task was to develop advanced product specifications with input from customers, listing laboratories and other standard-making entities. In the performance of Task 1, Omnion completed the following milestones and deliverables:

- m-1.1.2a Initiated lower-tier subcontract with SST.
- m-1.1.3a Completed resonant power module specification in conjunction with SST.
- m-1.1.1 Completed development of draft product specifications.
- m-1.1.2 Completed failure analysis of all Omnion three-phase IGBT units deployed since 1990.
- m-1.1.3 Completed customer review and comment on draft specifications with eight customers/users.
- m.1.1.6 Completed draft working product specifications.
- m-1.1.8 Completed Task1.
- D-1.1 Completed summary report of field failure experience.
- D-1.2 Completed final draft of product specifications.

A project start-up meeting was held on October 4, 1995 with NREL and Sandia personnel at Omnion's facilities.

Specifications for the core resonant converter were developed in conjunction with SST. Product specifications for the PCS were also developed. Representative Omnion product specifications and specifications from recent major procurements (PVUSA, Team-Up, and Sacramento

Municipal Utility District (SMUD)) were collected to serve as references. A draft of the 100-kW PCS specifications were completed in January 1996 based on Omnion's Series 3200 and 1996 draft Team-Up. Review and comments from the Technical Monitoring Team prior to our presenting this to key customers/users were requested and received.

Review of the product specifications with key customers/users was initiated. Omnion sales/marketing and engineering personnel conducted these interviews. To facilitate presenting the design and focusing the reviewer's attention on specific features, three documents were provided to each reviewer: 1) A system one-line drawing, 2) System specifications (see Appendix A), and 3) A matrix comparing the specification requirements of recent industry procurements (see Appendix B). The specification comparison matrix included the most recent SMUD three-phase specifications, the most recent Team-Up specifications, Amoco Enron's draft specifications and Omnion's single-phase Series 2400 product specifications. Walking each reviewer through the matrix and referring to the one-line diagram or system specifications when necessary proved to be an efficient method for obtaining detailed input. Each interview lasted between two and three hours. Comments from each reviewer were shared with the design team. Some examples of standard design features agreed upon included the National Electrical Code (IEEE 928, IEEE 929 and IEEE 519), the FCC Part 15 (Subpart A and B), an Emergency Stop and a dust proof enclosure. The need for a visible break disconnect was also identified through these analysis procedures. Customer/user feedback (See Appendix C) regarding features and qualities were incorporated in the PCS specifications.

A review and analysis of field failures experienced with Omnion's Series 3200 hard-switched IGBT product was initiated in March 1996 and completed in June 1996. Proper identification of past problems was helpful in solidifying the design of the Series 3400 product.

During the month of January 1997, Omnion participated in the UL industry work group to develop the 1741 standard for photovoltaic inverters. In addition, Omnion participated in the IEEE929 work groups of SCC21. The information gathered at these meetings was used in conjunction with the customer/users reviews for determining improvements to the product. Omnion then compared the product design with these standards.

Task 2 - Prototype Design and Fabrication

The goal of this task was to develop, fabricate and test a prototype PCS based on the product specification developed in Task 1. The following milestones and deliverables were completed during Task 2:

- m-1.2.7a Demonstrated core module high power operation at SST.
- m-1.3.1a Completed deployment of core module at SST.
- m-1.3.2a Completed prototype power conversion system design.
- m-1.2.3 Completed prototype power conversion system packaging.
- m-1.3.4a Completed final bill of material and component specifications for the prototype.
- m-1.3.5a Completed assembly of 100-kW Three-phase PCS prototype.
- D-1.3 Delivered sample photo of prototype system packaging.
- D-1.4 Delivered final bill of material.
- D-1.8 Received core resonant converter module from SST.
- D-2.2 Delivered outline of revised test procedures for the Series 3400 PCS.

The core resonant converter was developed in conjunction with SST. A draft of the Resonant Power Module specifications were prepared and forwarded to SST. The bridge (converter) power electronics combined with basic bridge control circuits (gate firing, etc.) form a core module. The draft specifications were reviewed in detail with SST personnel and then updated to serve as working specifications. A breadboard core module was designed and tested by SST at full voltage and current in December 1995. SST then shifted their focus to designing of the final control boards and the prototype. The core resonant converter printed circuit board features were reviewed with SST personnel in January 1996 to confirm adequacy and to assure compatibility with Omnion's master control functions. Particular attention was paid to interface specifications. During the development phase of the core resonant converter, monthly progress review meetings were held with SST personnel.

Midway through the development of the core resonant converter, SST ran into a serious problem with respect to clamp IGBT failure. SST personnel and the device manufacturer were puzzled by the failures since the device appeared to operate within specifications. Efforts to solve this obstacle resulted in a two-month delay in SSTs schedule. Core module performance testing remained on hold while the clamp problem was being worked on. The clamp problem was finally solved in May 1996. It appeared that the clamp IGBT failure was due to internal oscillation on the gate. After this obstacle was resolved, work at SST progressed normally. A prototype core resonant converter was delivered by SST in September of 1996 (See Figure 2-1).

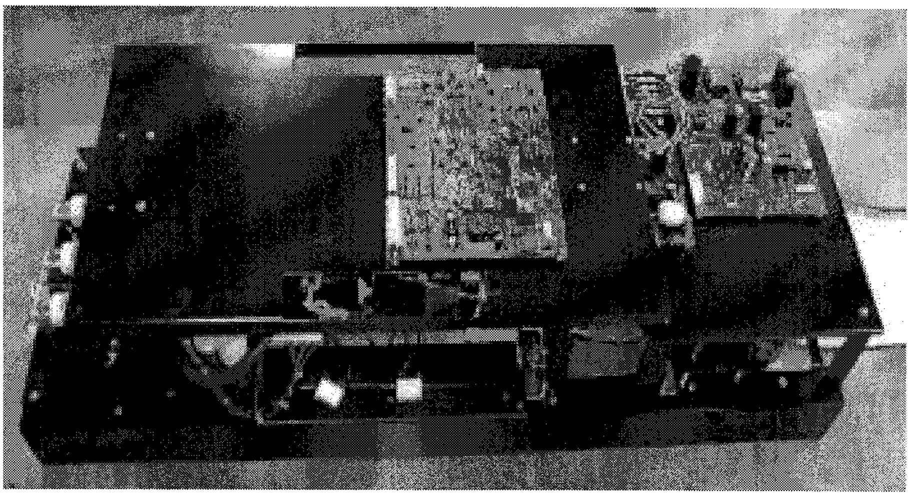


Figure 2-1 Resonant DC Link Core Module illustrating compact design.

SST started the development of the DC/DC converter, the "front end" of the core resonant converter, in September 1996. This DC/DC converter is used to step up the photovoltaic array voltage to the level that the core resonant converter needs to produce the appropriate AC voltage to the utility grid. A trade-off analysis was conducted to arrive at the final converter topology and a schedule for fabrication and test was developed. A prototype DC/DC converter was scheduled for delivery to Omnion in April 1997.

Circuit Board Designs: Design work was initiated on the Analog Interface printed circuit board in January and completed in December 1996. The prototype Analog Interface Board is shown in Figure 2-2. This board is used to convert high voltage signals to logic levels for input to the Master Control board. Work was also initiated in January on the system schematic and bill of material. Work on the Master Con

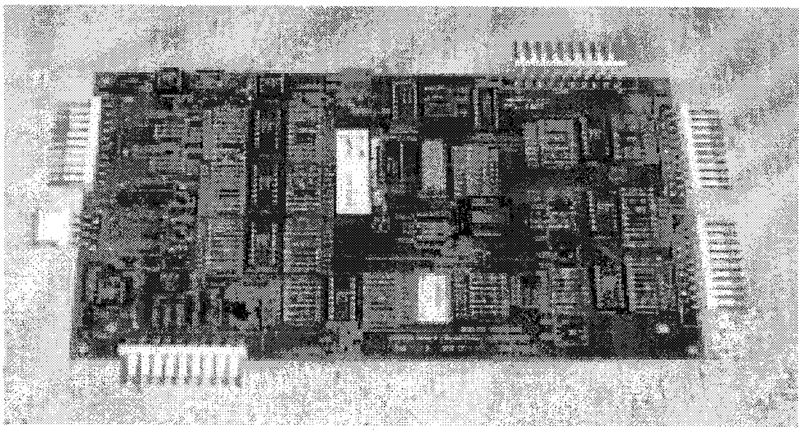


Figure 2-2. Analog Interface Board illustrating reduced parts count.

trol printed circuit board was initiated in February 1996 and completed in September 1996. The prototype Master Control Board, shown in Figure 2-3, is responsible for overall system control and, specifically, control of the core resonant converter module. Preparation of test procedures for the Master Control printed circuit board was initiated in June 1996. A state diagram was prepared to facilitate writing of the software. Software design was initiated in September 1996.

The prototype bill of material was released by engineering in June 1996. In stock materials were staged while other items were given to purchasing for procurement.

System Packaging: The system packaging work was initiated in February 1996. Packaging, control design, and core resonant converter module design are all highly interrelated, and therefore required simultaneous consideration. Progress made at SST on the final packaging of the core resonant converter module enabled Omnion to move forward with system packaging in August 1996. A modular T-slotted aluminum frame system, with aluminum side panels, was selected to readily permit optimization of component location within the enclosure. A preliminary cabinet layout was completed in September 1996.

Quality Audit: A quality audit on the core resonant converter was conducted by Omnion's quality assurance personnel in September 1996.

The report was shared with SST to enable improvements to be implemented on future units.

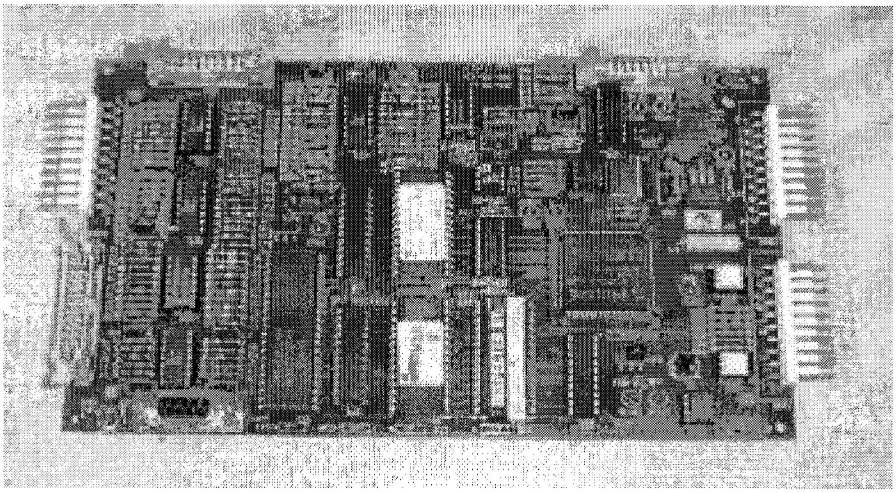


Figure 2-3. Master Control Board

The core resonant converter module, received from SST, was tested in October 1996. It was tested and operated in parallel with Omnion's utility service to ensure proper functioning.

Design of a Test Fixture: Test fixture design for the PCS control boards was initiated in December 1996. Software was written for the test fixture to verify the functionality of the controls. All the main system boards were tested in January 1997 using the completed test procedures. System tests started in February 1997 upon the completion of the system software and system test procedures. The majority effort of the software was to implement and debug the communication between different system control boards. This was completed in January 1997 along with all the fault handling routines, islanding routine, and sequencing routines.

Fabrication of the Prototype PCS: Fabrication of the prototype (See Figure 2-4) was completed in February 1997 and system tests were initiated. Preparation was made for the design of an additional test fixture that would be used as the main power source for power testing. Additional software routines including DC voltage monitoring, automatic power tracking, reference waveform generation and other system interfaces were completed in February 1997.

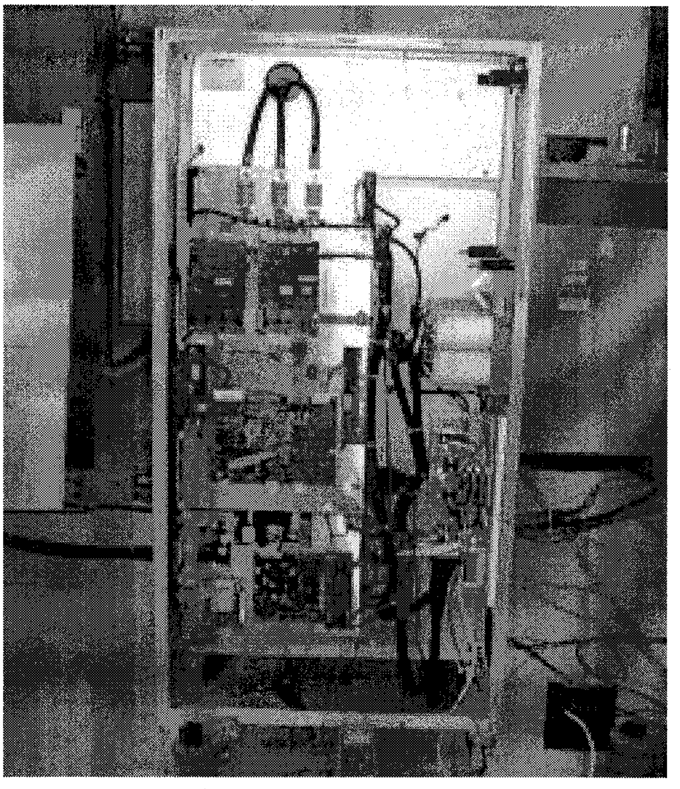


Figure 2-4. Prototype Series 3400 PCS illustrating compact cabinet layout

In March 1997, the prototype PCS was running as a utility grid connected system in excess of 70-kW. Core resonant converter efficiency of close to 98% was obtained. A graph of the core resonant converter efficiency is shown in Figure 2-5. Additional testing was conducted using the DC/DC converter along with the core resonant converter module. Problems uncovered during testing of the resonant converter slowed progress. These problems included protective function coordination within the core resonant converter module itself which resulted in the unit shutting down, communication problems between the core module and the master system controls which resulted in loss of communication under certain conditions and incorrect gains in the control loops which caused instability at certain power levels and the implementation of the hand-held pendant control interface. All issues were resolved with the exception of the hand-held pendant, which was expected to be completed in April 1997.

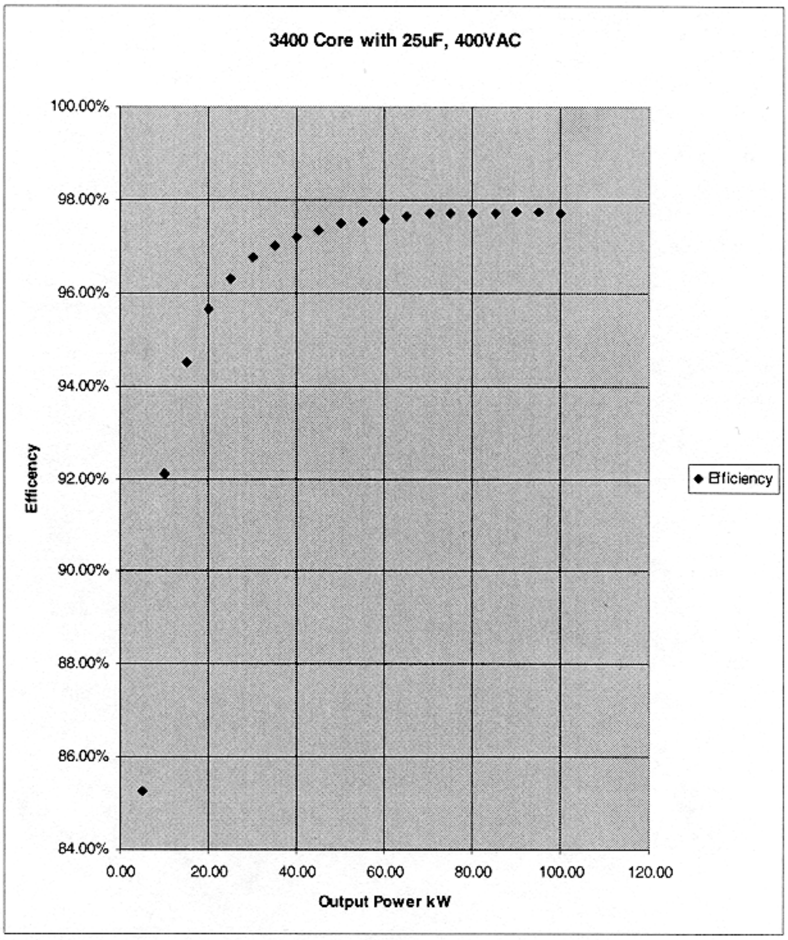


Figure 2-5. Resonant Converter Efficiency

Omnion completed the failure modes and effects analysis (FMEA) for the prototype Series 3400 PCS in April 1997 and forwarded it to SST for review. SST completed their review of the FMEA in May 1997. Omnion incorporated their comments and transmitted the FMEA along with the updated test plan for the Series 3400 on July 10, 1997.

Task 3 - Customer/User Demonstration and Review

Under Task 3, Omnion demonstrated operation of a prototype PCS to its customer/user group. At the conclusion of the demonstration, the customer/user group reviewed and critiqued the product specification identifying possible areas for improvement in the prototype 3400 PCS design. The following milestones were completed under Task 3:

- m-1.4.2 Completed 75-kW PCS prototype demonstration to customer/user group.
- m-1.2.5 Completed development of test procedures for the 100-kW PCS.
- D-1.7 Delivered pre-production product specifications.

The demonstration and customer/user group review was held on April 16, 1997. The prototype Series 3400 PCS, less the boost circuit, was brought up to full operating conditions for the customer review and demonstration. On April 17, 1997, the end of Phase I review was conducted with the technical monitoring team (TMT). Phase II of the project was also reviewed and Omnion received approval to move forward from the TMT.

Following the customer/user group review, work continued on testing of the Series 3400 PCS with emphasis on the boost section to improve its performance. A component failure occurred during continuous operation testing of the Series 3400 which caused failures in some of the surrounding components. Omnion removed the boost section and returned it to SST for repairs. An analysis of the failure showed that the clamp transformer had overheated and failed. The repaired boost section was received back from SST in July 1997. Another failure of the boost section in July 1997 required it to be sent back to SST for further debug and repair.

Phase II

Preproduction Model Development

In Phase II, Omnion worked to refine the design and packaging of the Series 3400 implemented manufacturing processes to reduce labor content and materials costs and produce two production models. The goals for the Series 3400 were to be able to meet the requirement for utility interconnected PV and offer reduction in cost with improved performance.

Task 4 - 3400 Pre-production Power Conditioning System Development

The goal of this task was to incorporate the recommended Series 3400 design improvements made by the customer/user group in Task 3. In performance of Task 4, Omnion completed the following milestones and deliverables:

- m-1.4.1 Completed updating of design documentation to “as-tested” status.
- m-1.4.3 Completed review and finalized pre-production product specifications.

- m-1.4.7 Completed Task 4 - 3400 Pre-production Power Conditioning System Development.
- m-2.1.1 Completed comparison between Omnion's Series 3200 and 3400 three-phase 100-kW power conversion system design.
- D-2.1 Delivered illustrated drawing of revised and repackaged PCS design.

In April 1997, Omnion met with SST to discuss recommended manufacturing, packaging and reliability improvements to the resonant core module. In June 1997, Omnion contracted SST to redesign the resonant core module packaging to allow heat to be more easily removed from the unit in an outdoor enclosure. SST completed their preliminary redesign of the core module packaging in July 1997 and Omnion continued working with SST to improve the packaging design. In August 1997, the resonant core module was retrofitted with a different set of inductors to improve the ability to package the core module in an outdoor enclosure. The new inductors are toroidally wound air core inductors which allow packaging in a smaller steel enclosure since the magnetic fields are contained within the toroid and therefore will not couple with the surrounding steel enclosure. The new toroid inductors were tested with the core module and found to be 0.5% less efficient than the previous iron core inductors. The small loss in efficiency was deemed acceptable because of the improvements made to the packaging design which yield a lower overall cost for the system. In October 1997, Omnion completed the redesign of the core module packaging and transmitted the revised design to the TMT on November 11, 1997.

In December 1997, Omnion completed the manufacturing plan for the Series 3400 PCS and transmitted it to the TMT on December 10, 1997. The manufacturing process for the Series 3400 was designed to minimize manufacturing cost while incorporating comprehensive quality control and quality assurance test and inspection of the product.

By December 1997, SST had still not resolved the problem with the boost section failures previously identified in Tasks 2 and 3. By this time, Omnion had also gained some additional experience with SST soft-switching converters from testing of two SST resonant core modules that Omnion had applied to a set of batteries for AC Battery Corporation. Multiple clamp device failures were experienced on the two SST core modules for AC Battery. With SST's assistance, Omnion eventually was able to determine the cause of the clamp device failures to be over-heating of the clamp IGBT. Testing at Omnion showed that the clamp IGBT heatsink had to be limited to 60°C. A 60°C limitation on clamp heat sink temperature meant that we could run 200 amps AC maximum out of a core module in a 40°C ambient. If the ambient is raised to 45°C, the limit is 150 amps AC, exactly what the prototype is rated at. At 50°C, the core module de-rates to 100 amps AC. This was too severe of a derating for our application. As an example, in a hard-switched application the same IGBT that is used in the clamp could typically run on a heat sink with a 100°C temperature. In addition, to be cost effective, Omnion's design goals were to push up to 255 amps out of a similar bridge that used 300 amp devices.

This newly found fault along with the inability of SST to produce a working boost section has caused Omnion to review its soft-switching path. While we feel that soft switching continues to have great possibilities, in the short term this clamp device problem limits its application to low ambient temperature applications. Omnion began looking at alternate solutions that would allow for a product that meets all project goals. All Series 3400 hardware development work on the project was stopped in December 1997, pending approval of the new path by the TMT.

On December 16, 1997, Omnion transmitted a proposal to the TMT to pursue a hard-switched solution for the PVMaT contract. In February 1998, Omnion completed an updated Statement of Work for the new hard-switched solution and forwarded it to the TMT for final approval.

Phase III

The change from soft-switching technology (Series 3400) to hard-switching technology (Series 3300) produced several benefits. The first benefit was the use of field proven hard-switching technology. The Semikron Skiip bridge was used for the 3300 power train. The Skiip bridge is a high volume production bridge which is competitively priced and offers may different capacities. The flexible OMNION control board set can be used with different capcities of the Skiip bridge to produce multiple size models. The Skiip bridge packaging offers bettery thermal coupling which reduces the cooling requirement and improves the temperature proteciton of the power devices. The Skiip bridge includes integrated current sensors which can be available for control purposes, thereby eliminating the need for additional sensors.

Task 5 - 3300 Pre-production Power Conditioning System Development

In Task 5, Omnion revised and repackaged the prototype PCS design utilizing hard-switched technology. The goal of this task was to redesign the prototype PCS to meet the defined performance improvements for the PVMaT contract. The following milestones and deliverables were completed during Task 5:

- m-2.5.1 Completed revision of the PCS prototype design to incorporate the Skiipack hard-switched technology.

- m-2.5.2 Completed redesign of the prototype packaging for the new core module.
- m-2.6.2 Completed revision of Operation and Maintenance (O&M) Manual for production of 100-kW, three-phase, power conversion system product.
- m-2.5.3 Completed Task 5 - Development of Revised and Repackaged Design for the Series 3300, Incorporating Improved Hard-Switched Design to Meet the Defined Performance Improvements.
- D-2.1 Delivered illustrated drawing of the revised and repackaged prototype PCS design.

On March 10, 1998, Omnion received approval from the TMT to proceed with the proposed hard-switched solution for the 100-kW, three-phase, utility interconnected photovoltaic converter deemed the Series 3300. A specification for the Series 3300 PCS (see Appendix D) was completed in March 1997 and transmitted to the TMT on April 20, 1998.

A one-line diagram for the Series 3300 PCS was completed in April 1998 and transmitted to the TMT on May 21, 1998. In addition, a preliminary bill of materials was developed and key component specifications were developed and issued for purchase order.

The Semikron Skiipack (**S**emi**K**ron **i**ntegrated **i**ntellegent **P**ower) power bridge, ordered for the new Series 3300, was received in May 1998 and work began on the packaging design.

In June 1998, Omnion completed the development of the Series 3300 PCS schematics and system packaging design. In addition, the bill of materials for the prototype Series 3300 was released. In the final packaging design(see Figure 2-6) two compartments constructed with bolt-on panels were implemented for the Series 3300 enclosure. One compartment to house the output isolation transformer and inductors, the other compartment to house the power bridge, control board set, and other control components. Other optional components, such as the AC and DC disconnects, would be mounted on either side of the enclosure.

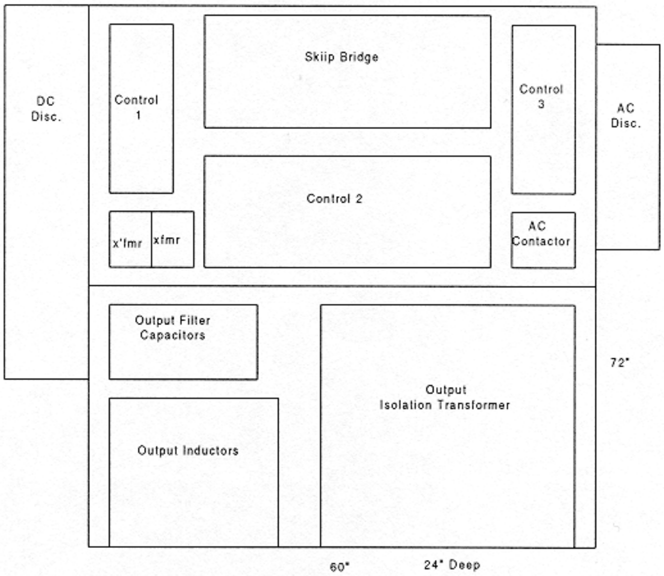


Figure 2-6. Series 3300 Packaging Layout

Task 6 - Test Procedures and O&M Manual

Under Task 6, Omnion refined the product test procedures and drafted a comprehensive, user- friendly, Operation and Maintenance (O&M) Manual for the new Series 3300 PCS. The following milestones and deliverables were completed during Task 6:

- m-2.6.1 Completed revision of the test procedures incorporating quality control steps to ISO 9001 standards.
- D-2.2 Delivered outline of the revised test procedures.
- D-2.3 Delivered draft O&M Manual for the new prototype Series 3000 PCS.

In October 1998, following completion of the Series 3300 factory testing, Omnion completed updating the test procedures and completed the new user-friendly O&M Manual.

Task 7 - Manufacturing Development

The goal of this task was to design and develop the manufacturing process for the new Series 3300 PCS. This included development of suitable jigs and fixtures for assembly and test. In the performance of Task 7, Omnion completed the following milestones and deliverables:

- m-2.7.1 Completed re-design of manufacturing tools, jigs, and fixtures for the Series 3300 PCS.

- m-2.7.2 Completed preliminary evaluation of the manufacturing equipment.
- D-2.4 Delivered illustrated drawings/general schematics of designs for tools, jigs, and fixtures.
- D-2.4a Delivered Lessons Learned Report summarizing the results of the discontinued Series 3400 PCS development.
- D-2.6 Delivered summary report detailing assessment results of the pre-production model and manufacturing equipment performance.
- D-2.7 Delivered diagrams/illustrations of the manufacturing process with supported shop floor drawings, material flow, and process stations.

In June 1998, Omnion completed and delivered the Lessons Learned report (see Appendix G) identifying the lessons learned from our efforts to incorporate soft-switching into our next generation three-phase, utility interconnected photovoltaic power conversion system.

In October 1998, Omnion completed the re-design of the manufacturing tools, jigs, and fixtures for the Series 3300. In addition, Omnion completed preliminary evaluation of the manufacturing equipment and delivered a summary report detailing assessment results of the pre-production model and manufacturing equipment performance including diagrams/illustrations of the manufacturing process with supported shop floor drawings, material flow, and process stations. See Appendix H for copies of the Series 3300 pre-production summary report and manufacturing process diagram.

Task 8 - Fabricate and Test Pre-production Model

In the performance of Task 8, Omnion completed the assembly and evaluation testing of the prototype Series 3300 PCS. These evaluation tests were performed to verify that the 100-kW, three-phase, Series 3300 PCS meets or exceeds the specifications and defined performance improvements. The following milestones and deliverables were completed under Task 8:

- m-2.8.1 Demonstrated the Series 3300 PCS performed to specifications.
- D-2.5 Delivered factory test results of the pre-production 100-kW, three-phase, Series 3300 PCS.

In July 1998, production of the pre-production Series 3300 started. The enclosure panels were received and assembled to form the two compartment enclosure for the Series 3300. Key components were mounted both inside and outside the enclosure. See Figures 2-7 through 2-9 for photographs of the production work on the Series 3300.

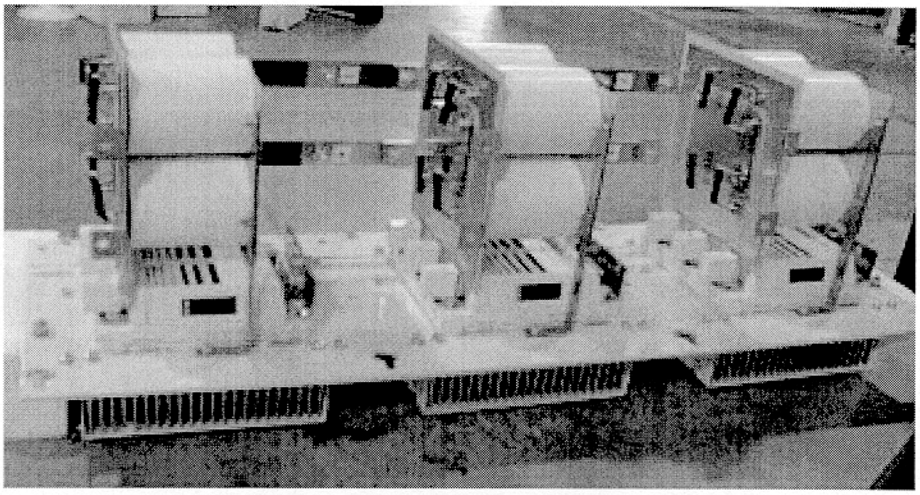


Figure 2-7. Series 3300 Skiipack Power Bridge illustrating modular bridge assemblies and sub-assemblies used.

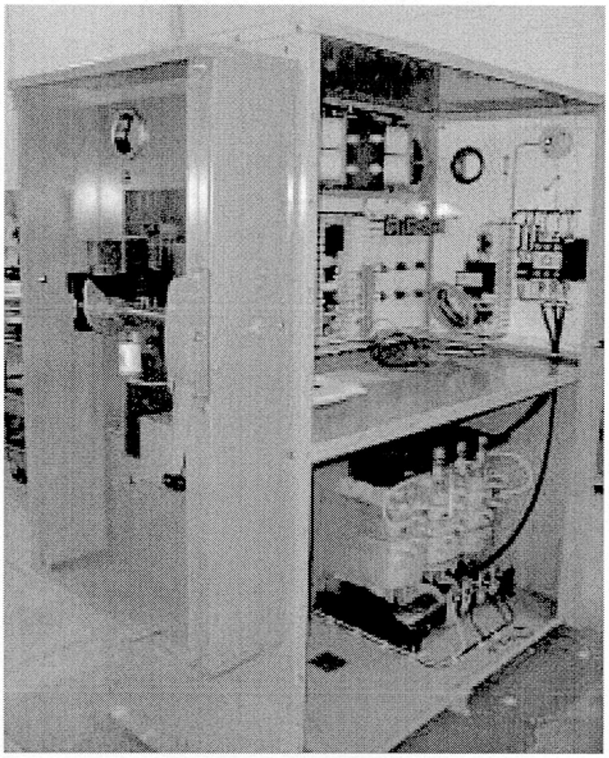


Figure 2-8. Series 3300 Production Cabinet (based on customer feedback) Front-Left View

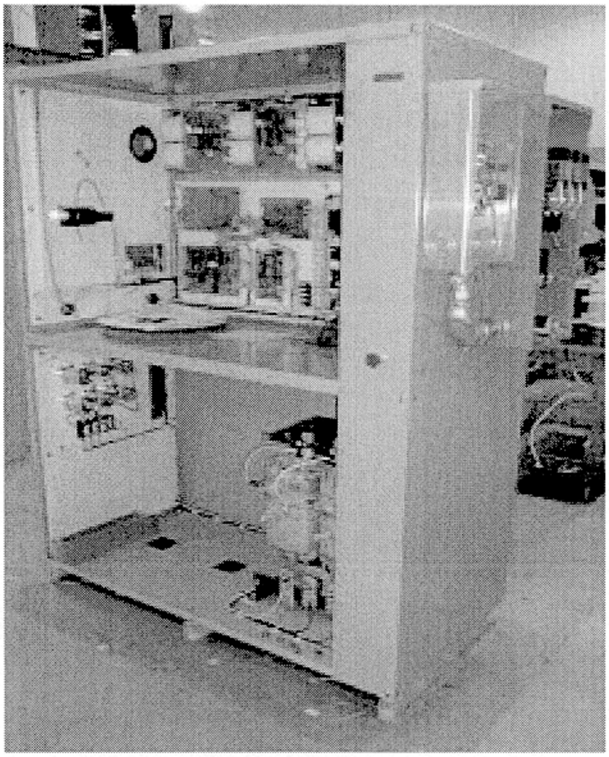


Figure 2-9. Series 3300 Production, Front-Right View

Production on the pre-production Series 3300 unit was completed in early August 1998 and system testing began. See Figures 2-10 and 2-11 for photographs of the completed pre-production Series 3300 unit.

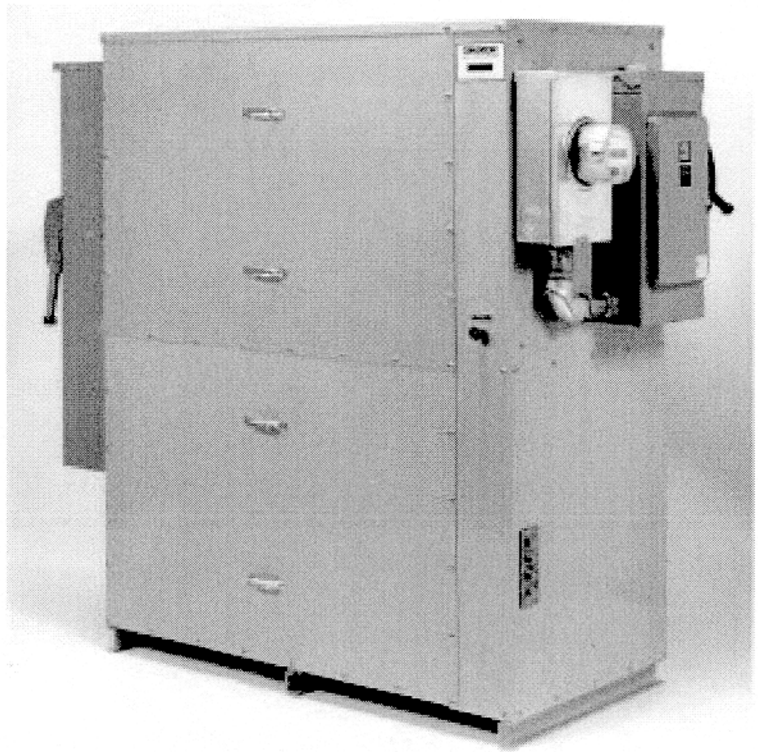


Figure 2-10. Series 3300 Photovoltaic PCS, Front View

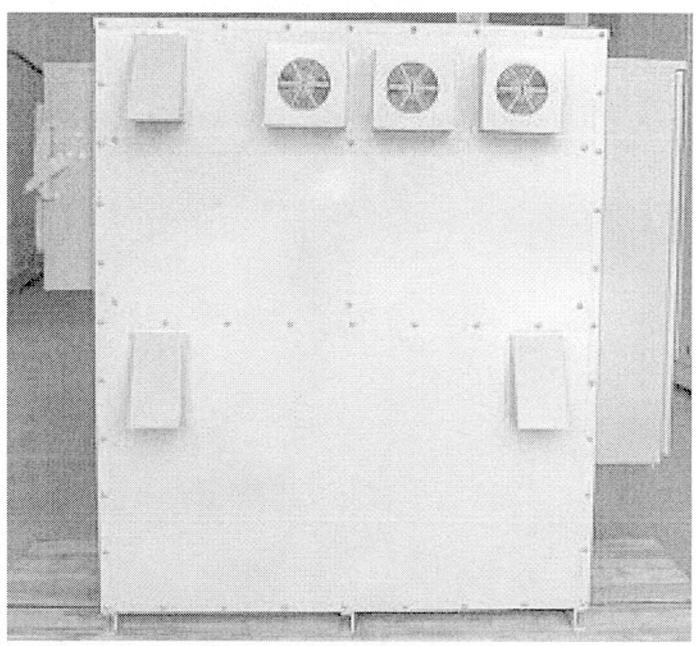


Figure 4-11. Series 3300 Photovoltaic PCS, Rear View

In the cutaway front view shown in Figure 2-12 below, key components of the Series 3300 PCS are numbered/lettered for identification:

1. One (1) Series 3300 Power Conversion System (PCS) including:
   a) Main DC Disconnect
   b) Self Commutated IGBT Power Converter Bridge Assembly
   c) Solid State PCS Controls
   d) RS232 Interface
   e) DC Ground Fault Detection
   f) Air-Core Inductors
   g) Filter Capacitor Assembly
   h) 208/120: 480 Vac Isolation Transformer
   i) AC Contactor Assembly with Soft Start
   j) EMI Filter
   k) Fused AC Disconnect
   l) AC Watt-Hour Meter
2. One (1) Outdoor Enclosure including:
   m) 20 character, 2 line, backlit LCD display
   n) E-Stop/Reset Push-button Switch

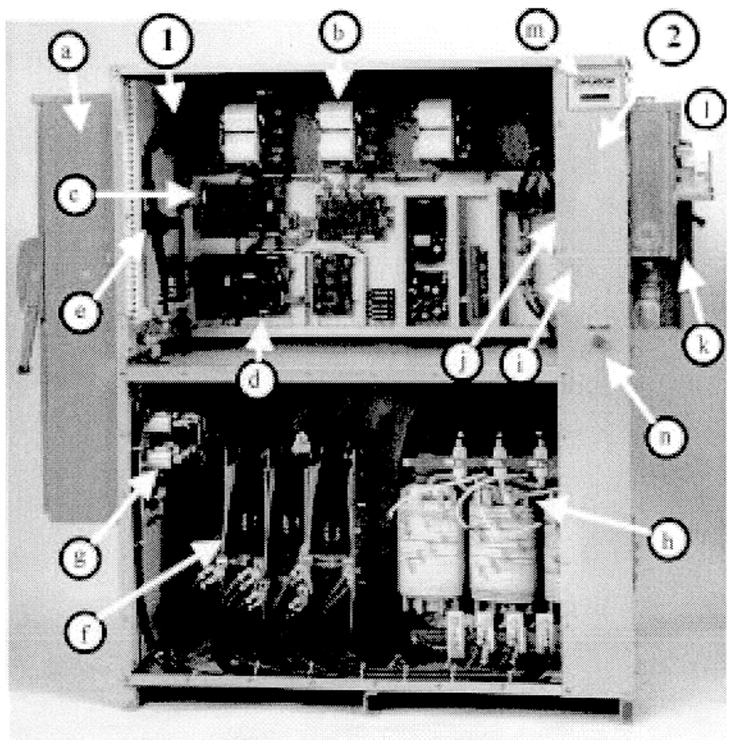


Figure 4-12. Cutaway Front View of the Series 3300 PCS

A problem with the Series 3300 current and voltage regulators was discovered during the initial at power tests. The current regulator board takes reference current waveforms from the master control board and develops switching commands for the IGBTs on the power bridge. In August 1998, the current regulator board was replaced with a different type of regulator which corrected the problem.

The voltage regulator controls DC voltage by increasing or decreasing the output power. During the initial testing the voltage regulator was found to be unstable at low power levels. The problem was found to be due to an interaction between the voltage regulator, which was implemented in software, and a power supply's voltage regulator. This problem was corrected in September 1998 by implementing a new hardware circuit for the voltage regulator.

In September 1998, when the Series 3300 DC input was changed from a test DC supply to Omnion's 9-kW photovoltaic array, a problem was found where the Skiipack power bridge would fault on power up. The problem was found to be electrical noise from the AC contactors on power up. This problem was corrected by increasing the time constant on the detection circuit from 0.1 μS to 100 μS.

Testing of the pre-production Series 3300 unit was completed in September 1998, and the system was shipped to Sandia National Laboratories on September 30, 1998 for additional testing and evaluation.

UL Listing of the Series 3300 is planned to begin following completion of the Sandia testing.

Task 9 - Presentations and Publications

In Task 9, Omnion conducted semi-annual progress reviews and presented project progress to the program participants at the 1998 NCPV Conference held September 8-11, 1998 in Golden, Colorado.

Task 10 - Project Management and Reporting

In Task 10, Omnion completed and delivered monthly technical status reports, annual executive technical summary report, annual technical progress report, quarterly cost plans, subcontract management summary report, small business and disadvantaged business plan reports, and provided overall contract and technical management during the project.

Conclusions

Production costs for the pre-production Series 3300 PCS unit give a positive indication that the cost objective of reducing the total manufacturing cost from approximately $0.50/watt to $0.25/watt for a nominal 100-kW Series 3300 PCS, when built in production lots of 100 units, will be able to be met.

No major failures of the pre-production Series 3300 PCS were experienced during the intensive factory testing regime. This is a positive indicator, and Omnion is optimistic, that the reliability objective of 40,000 hours mean time between failures (MTBF) will be able to be achieved for the Series 3300 PCS.

The pre-production Series 3300 PCS has demonstrated through factory testing that it successfully achieved the performance objective of improving the converter efficiency from 95.5% to 96.5%. Figure 2-13 shows that a peak converter efficiency of 96.79% was achieved for the pre-production Series 3300 PCS.

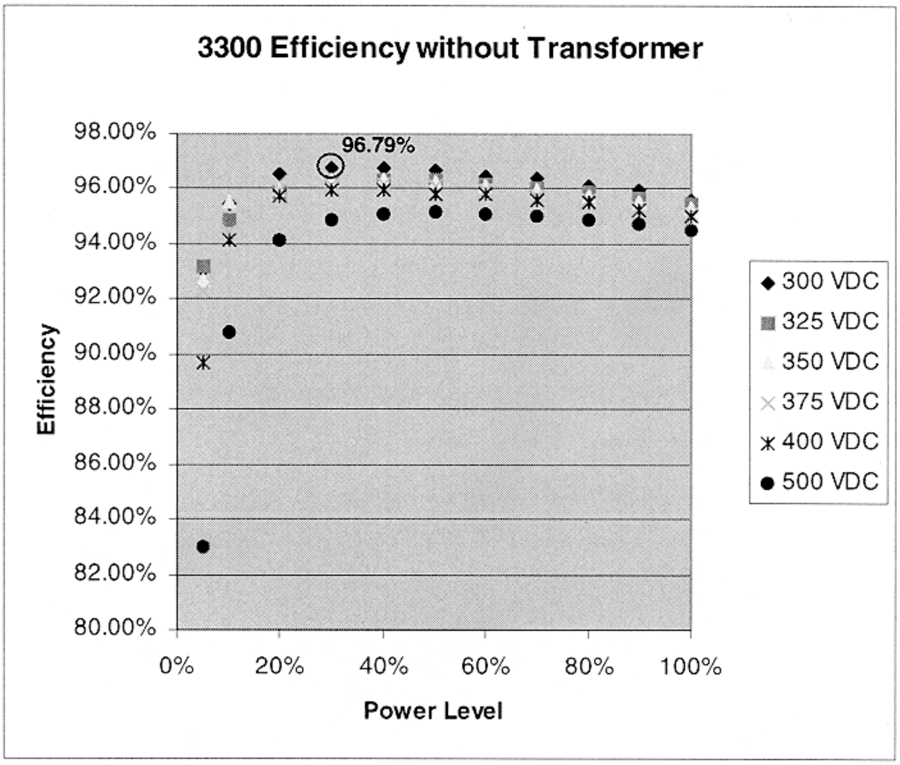


Figure 2-13. Series 3300 Converter Efficiency

Testing for electromagnetic interference is currently being performed on the pre-production Series 3300 PCS at Sandia National Laboratories. Omnion will evaluate whether the Series 3300 PCS meets the performance objective of meeting FCC regulations for electromagnetic interference when the Sandia testing has been completed.

Test measurements for audible noise were made during factory testing of the pre-production Series 3300 PCS unit. Audible noise levels of up to 66 dBA were recorded at a distance of two meters from the Series 3300 enclosure. While the performance objective of reducing the audible noise to below 60 decibels was not achieved, Omnion was able to significantly reduce the audible noise level to below the 74 dbA level of the previous generation Series 3200 PCS product.

The hard-switched solution presented in the Series 3300 PCS has successfully been able to achieve most of the design objectives originally identified for the soft-switched Series 3400 PCS. In addition, with the exception of a patented resonant power bridge, the Series 3300 PCS has all the product features of the Series 3400 PCS. See Table 2-1 for a comparison of the Omnion Series 3300, Series 3400, and Series 3200 PCS product features.

Feature	3300	3400 (prototype)	3200
Patented Resonant Power Bridge	No	Yes	No
IGBT Phase Leg Over-Current	Yes	Yes	No
IGBT Desaturation	No	No	No
Bridge Over-Temperature Protection	Yes	Yes	Yes
LCD Display to Show Operating Status and Analog Data	Yes	Yes	Yes
Power Supply Monitor	Yes	Yes	Yes
Over and Under Voltage - User Adjustable Parameters	Yes	Yes	Yes
Over and Under Frequency - User Adjustable Parameters	Yes	Yes	No
Synchronize to Utility	Yes	Yes	Yes
Low Acoustic Noise	Yes	Yes	No
Low EMI, FCC part 15	Yes	Yes	No
Low Current Harmonic Distortion	Yes	Yes	Yes
Easily Installed Standard Package	Yes	Yes	No
Passive Cooling	No	No	No
RS232 Port	Yes	Yes	No

Table 2–1: Comparison of the Omnion Series 3300/3400/3200 PCS

Feature	3300	3400 (prototype)	3200
DC Ground Fault - User Adjustable	Yes	Yes	Yes
AC Contactor	Yes	Yes	Yes
DC Contactor	No	No	Yes
Circuit Breaker	No	No	Yes
Data Available on RS232 Port:			
VDC	Yes	Yes	No
VAC - A Phase	Yes	Yes	No
VAC - B Phase	Yes	Yes	No
VAC - C Phase	Yes	Yes	No
Ground Fault Current	Yes	Yes	No
Heat Sink Temperature	Yes	Yes	No
Commanded Amps AC	Yes	Yes	No
Status of System	Yes	Yes	No
Commands Available Over RS232 Port:			
Shutdown and Lockout	Yes	Yes	No
Reset	Yes	Yes	No
Status	Yes	Yes	No
A/D Data Dump	Yes	Yes	No

Table 2–1: Comparison of the Omnion Series 3300/3400/3200 PCS

The Omnion Series 3300 Three-Phase, Utility Interconnected, Photovoltaic Power Conversion System embodies the goals and the vision of the PVMaT Phase 4A program, focusing on product-driven manufacturing research and development, and emphasizing improvement and cost reduction in the manufacture of full system PV products.

Appendix A - Proposal for a 100-kW Utility Interconnected Photovoltaic System

Scope

The contract consists of two one-year phases. During the first phase, OMNION will develop the specifications, then design, build and test a prototype 100-kW, three-phase power conversion system (PCS). In Phase II, OMNION will finalize the revised and repackaged design for the 100-kW PCS product. OMNION will also conduct tests on modified manufacturing equipment, and conduct a pre-production run of the prototype 100-kW, three-phase PCS.

At the conclusion of Phase II, OMNION will have a production-model power conversion system submitted for UL certification. This PCS will meet the requirements for utility-interconnected PV and offers reduction in costs with improved performance. In addition, OMNION will develop an Operation and Maintenance (O&M) Manual for the new PCS. These developments will be conducted in the tasks described below.

Phase I

Task 1 - Specification Development

Under this task OMNION will prepare an advanced product specification with input from customers, certification laboratories and other standard-making entities. This will be accomplished in Tasks 1.1 - 1.6. Field experience gained to date with related products will be analyzed for its relevance to product specifications. The result of this task will be a working advanced product specification to be used as a benchmark during the balance of the development effort.

Subtask 1.1 - Draft Advanced Product Specification

Omnion shall prepare a straw man nominal 100-kW, three-phase power conversion product specification for use in the Tasks 1.3, 1.4, and 1.5 below. The draft product specifications shall be prepared based on Omnion's understanding of customer preferences and current technological trends. Omnion's current three-phase product specifications and its expectations regarding the improvement that can be made in this development should serve as a starting point for this effort.

Omnion intends to incorporate the following features into the Series 3400 product: Resonant DC link technology developed and patented at the University of Wisconsin, reduced EMI compatible with FCC Part 15, Subpart B requirements, increased efficiency (96 -97% at rated output), innovative thermal design made possible by lower switching losses including the possibility of passive cooling of the IGBTs, high density system packaging suitable for outdoor installation, a highly integrated control to minimize parts count and cost, and a communication port such as a RS232 bus for remote monitoring and control.

Subtask 1.2 - Analyze Field Failures Experienced to Date

Omnion shall conduct a thorough analysis of field failures experienced to date with Omnion's IGBT technology hardware to better understand where design improvements are needed. Since 1990 Omnion has shipped 20 three-phase PV PCSs ranging from 15 kilowatts to 275 kilowatts employing its three-phase IGBT technology. Collectively, these units have amassed 34 machine-years of operation. The failures and down-time that have been experienced provide an invaluable guide for where design improvements are needed. All failures and outages will be analyzed and categorized using Omnion's service records and customer log books as necessary. The analysis of field failures for Omnion's three-phase, photovoltaic, IGBT products shall list and categorize all known outages, their cause, and the corrective action taken. Conclusions and recommendations shall be prepared to guide further development efforts.

Subtask 1.3 - Present and Review Product Specification with Key Customers/Users

Omnion shall obtain feedback from customers/users regarding the features and qualities they would most prefer to see incorporated in a new PCS product. One salesperson and one engineer from Omnion will visit six to eight key customer/users (See Appendix C) to review the draft specification prepared in Subtask 1.1. Comments from each visit shall be catalogued and sorted. An informal report shall be prepared which lists and summarizes the comments received and which recommends specific items for incorporation into the draft specification.

Subtask 1.4 - Present and Review Product Specification with IEEE Protection & Relaying Committee

Omnion shall obtain input from the IEEE Protection & Relaying Committee regarding the PCS product specification with particular emphasis on utility protection features. Omnion shall encourage the committee to consider taking actions that could lead to standardization of interconnection requirements for all utilities, shall present a draft specification to that committee, and assist the committee as practicable in working to this end. Comments regarding the specification shall be recorded, and the need for standardization of utility interconnection requirements shall be presented for the committee's further consideration. Omnion will prepare an informal report listing and summarizing the comments received, including recommendations regarding specific items for incorporation into the draft product specification.

Subtask 1.5 - Present and Review Product Specification with a Certification Laboratory

Omnion shall obtain input from a recognized certification laboratory, such as UL or ETL regarding conformance of the specification with existing standards. If specific standards do not exist for this type of product, Omnion will discuss with that agency and other appropriate representatives (including NREL and SNL) regarding how a cooperative effort might be established to create such standards. To accomplish this, Omnion shall contact UL to schedule a review of the draft product specification. Omnion shall prepare an informal report listing and summarizing the comments received and recommending specific items for incorporation into the draft specification.

Subtask 1.6 - Draft Final Working Product Specification

Omnion shall prepare a working specification to serve as a benchmark in the design and fabrication of an advanced three-phase PCS. Using the draft specification prepared in Subtask 1.1, the failure analysis prepared in Subtask 1.2 and the comments received in Subtasks 1.3, 1.4 and 1.5, Omnion shall prepare a working specification to serve as a baseline in the development of the new power conversion system. The specification baseline shall incorporate relevant and realistic suggestions received from reviewers that are consistent with the fielding of a standard, baseline power conversion product.

Task 2 - Prototype Design and Fabrication

Under Task 2, Omnion will develop, fabricate and test a prototype converter based on the product specification developed in Task 1. This will be accomplished in Tasks 2.1 - 2.9. The results of this task will be a fully tested and documented advanced PCS.

Subtask 2.1 - Develop Core Resonant Converter Technology

A resonant DC link converter bridge with integrated soft switching controls, collectively referred to as a "core module", shall be specified and developed. The majority of the development work will occur at Soft Switching Technologies (SST) an Omnion lower-tier subcontractor. The specification for the core module shall be developed jointly by Omnion and SST. A nominal 100-kW, three-phase resonant PV converter bridge design shall be completed including power and control schematics, bills of material, and component specifications. Bench testing shall be completed as necessary to confirm the viability of the design concepts.

Subtask 2.2 - Design Prototype Power Conversion System

Omnion shall design the balance of the PCS including switchgear, thermal management systems, status indicators and diagnostics. The design shall be in keeping with the working specification and using the core module design developed in Subtask 2.1 above. Operating software shall be written to control the overall converter operation, to perform self-diagnostic procedures, and to communicate with the user. The PCS design documentation, such as control and power circuit schematics, bills of material, operating software and logic diagrams, shall be included.

Subtask 2.3 - Design Prototype System Packaging

Omnion shall develop an enclosure for the PCS circuitry suitable for outdoor use in the United States and its territories. The design of the enclosure will consider cost, ease of assembly, ease of shipping, ease of installation, ease of servicing, as well as protection of all circuitry to maximize the mean time between failures. Weight and volume of the system will be minimized consistent with durability, ease of assembly, ease of servicing, and minimum cost parameters. Particular attention will be paid to thermal management in that system functionality is impacted at low temperatures while component life is impacted at high temperatures. The design shall attempt to maintain ambient temperatures for all power electronic components between -10 and +120 degrees Fahrenheit. Passive cooling shall be employed if possible to improve reliability, reduce tare losses and minimize cost. A prototype enclosure design, such as preliminary identification of internal subassembly construction, shall be provided.

Subtask 2.4 - Interact with Vendors to Optimize Component Selection/Specifications

Omnion shall identify preferred components and component specifications for both commercially available and built-to-specification items, for minimum cost, maximum performance, and acceptable availability. For commercially available components, vendors or their representatives will be contacted to discuss and review the suitability of their offerings for incorporation into the design. Function, reliability, performance, cost and availability will all be considered. In the case of vendor candidates that would supply built-to-specification components, an engineer and a buyer representative shall travel to the vendor's site to discuss and review the vendor's ability to provide the particular component. Wherever practicable, multiple sources shall be identified for a particular component. This work shall be conducted in parallel with Subtasks 2.2 and 2.3 above. A final bill of material for the prototype design along with all component specifications shall be prepared. The bill of material shall be costed with prospective vendors identified for all components.

Subtask 2.5 - Conduct Failure Modes and Effects Analysis

Omnion shall identify failure modes and consequential effects for the PCS prototype design and provide feedback to the design team for Subtask 2.2 to enable the design to be improved. The PCS design as developed in Subtask 2.2 and as packaged in Subtask 2.3 above shall be analyzed in detail for possible failure modes. The reliability of all components shall be scrutinized considering how they are being applied and given the environmental conditions to which they will be subjected. Potential problem areas shall be referred back to the design to permit development of alternative solutions. This Subtask must necessarily lag Subtasks 2.2 and 2.3 but shall, nonetheless, be carried out on an interactive basis. An informal report shall be completed identifying the PCS failure modes, corrective actions, or modifications to the design.

Subtask 2.6 - Develop PCS Test Procedures

Omnion shall prepare comprehensive test procedures for critical components, sub-assemblies and the completed unit to ensure proper operation under all operating conditions that can be reasonably simulated. Preliminary test procedures shall be drafted by the design engineers for all printed circuit boards, bridge assemblies and the complete unit. Component and subassembly test procedures shall be prepared as appropriate for the overall testing of the equipment.

Subtask 2.7 - Assemble Power Conversion System Prototype

Omnion shall assemble the PCS prototype for testing purposes, gain experience in the assembly of the hardware and provide feedback to the engineering team regarding possible improvements. The bill of material prepared in Subtask 2.4 above shall be used in procuring the necessary materials for construction of the prototype. Wherever possible, long-lead items shall be ordered in advance to avoid or minimize delays in the assembly of the prototype. Subassemblies, including printed circuit boards, shall be passed to the test department when completed. Throughout the assembly process notes will be kept regarding design modifications which could potentially reduce assembly time or improve product reliability. A completed prototype ready for testing shall be built. An informal report listing recommendations to engineering for design modifications shall be provided.

Subtask 2.8 - Test Power Conversion System Prototype

Omnion shall test all aspects of the prototype PCS, including performance as well as functionality, for conformance to the working specification. Using the test procedures developed in Subtask 2.6 above and the power supplies, test equipment and instrumentation in Omnion's test department, the prototype shall be tested to determine that it both functions properly and meets the performance objectives set forth in the working specification. An extended heat run shall be conducted at elevated ambient temperature as called for in the product specifications (110 - 120°F) to identify thermal hot spots and breakdowns. Testing at extreme low temperatures shall be conducted as permitted by Wisconsin winters (-10 to -20°F is typical). The operation and performance of the prototype PCS shall be characterized. Any design problems encountered will be identified and options for their possible resolution in the future will be defined.

Subtask 2.9 - Prepare Design Documentation

Omnion shall bring all design documentation up to an "as-tested" status. Design documentation prepared in Subtasks 2.1, 2.2 and 2.3 shall be reviewed and updated to conform to the equipment as of completion of testing. All design modifications made in the course of testing shall be incorporated. All drawings shall be prepared on Omnion's CAD system. Bills of material shall be presented as they are used in Omnion's computerized inventory control system.

Task 3 - Customer/User Demonstration and Review

OMNION will demonstrate operation of the prototype photovoltaic power conversion system to the customer/user group, listed in Appendix C, at Omnion's facilities upon completion of factory testing. At the conclusion of the demonstration, all participants will review and critique the baseline product specification developed in Task 1. This will be accomplished in Subtasks 3.1.- 3.2. The result of this task will be an informed customer/user group and a list of possible areas for improvement in the prototype photovoltaic power conversion system's design.

Subtask 3.1 - Demonstrate Prototype to Customer/User Group

Omnion shall demonstrate operation of the prototype to the customer/user group at Omnion's facilities. Upon completion of factory testing (Subtask 2.8 above), a mutually-convenient date shall be set for the customer/user group to travel to Wisconsin to observe operation of the prototype. Critical steps in the test procedures shall be repeated to demonstrate system operation and performance. The hardware shall be reviewed in detail to ensure a good understanding on the part of all participants what the implications are of the requirements contained in the working specification.

Subtask 3.2 - Review and Finalize Product Specification

Omnion shall improve the product specification based on the experience gained with the prototype. The working specification shall be reviewed in detail with the customer/user group for possible improvements. Changes shall be considered for cost, operational or performance reasons. Omnion staff shall present data regarding trade-offs to assist the group in making decisions. In addition to reviewing the specification, suggestions and recommendations shall be discussed for improving the implementation of the specification. This preproduction product specification and a list of recommendations shall be used for improving the prototype design for consideration by the design team.

Phase II

Task 4 - 3400 Preproduction Power Conditioning System Development

Under task 4, OMNION will incorporate changes in Task 3 in the PCS product and specification. This will be accomplished in Tasks 4.1.- 4.3. The result of this task will be a revised and repackaged design.

Subtask 4.1 - Finalize Preproduction Model Schematics/ Component Specifications

Omnion shall improve and refine the preproduction PCS schematics and component specifications based upon input received in Task 3. Omnion shall revise and modify the prototype design to incorporate any changes in specifications and/or improvements identified in Task 3. Particular attention shall be paid to reducing manufacturing cost and maximizing product reliability.

Subtask 4.2 - Finalize Preproduction Model Packaging

Under this subtask, Omnion shall initiate improvements and refinements to the prototype packaging for minimum manufacturing cost and maximum product reliability. Omnion shall redesign the PCS packaging to further reduce cost and assembly time without compromising product reliability. These modifications will include minimizing the number of printed circuit boards, locating components to minimize wire-runs, and designing wiring harnesses to replace discrete wiring. Isolating access areas for customer interconnection of input and output wiring shall be reviewed and considered for possible incorporation in the design.

Subtask 4.3 - Interact with Vendors to Optimize Component Selection/Specifications

Omnion's engineering and procurement personnel shall meet with prospective vendors to explore alternatives to minimize cost while enhancing reliability. Consideration shall be given to certification laboratory requirements to ensure compliance of both the components and the overall design. The result of this subtask shall be the comparison of improvements of the 3300 to the 3200, including change in parts count, size changes and other design features.

Task 5 - 3300 Preproduction Power Conditioning System Development

Under Task 5, Omnion shall redesign the core module using hard-switched technology utilizing a highly integrated Skiipack Power Bridge from Semikron. See Appendix D for the new Series 3300 PCS Specification. The Skiipack offers full-scale integration that reduces size, cost and development time. It also offers optimal thermal management with an integrated heatsink, over-temperature and short-circuit protection with built-in sensors. This will be accomplished in Tasks 5.1 - 5.3. The results of this task shall be a revised and repackaged design to meet the defined performance improvements. See Appendix E for a comparison of the Omnion Series 3300 and Series 3200 PCS. Appendix F identifies the Series 3300 PCS benefits relative to the Omnion Series 3400 PCS.

Subtask 5.1 - Finalize Preproduction Model Schematics/ Component Specifications

Omnion shall revise and modify the prototype design to incorporate the hard-switched core module. The result of this subtask shall be a prototype PCS with the new core module. The following work will be performed:

1. Thermal Calculation/Sizing/Check Price & Delivery of Bridge
2. Obtain Bridge Technical Information
3. Design Bridge Interface
   a) Gate Firing/Regulator Board
   b) Layout regulator Board
   c) PQ Boards Modification
4. Cost Estimate of Board Set
5. Design Laminated Bus
   a) Capacitance Calculation
   b) Layout Laminated Bus
6. Design Snubber
   a) Layout Snubber Circuit
   b) Integration into Laminated Bus
7. Cost Estimate of Laminated Bus
8. Evaluate EMI Filters
9. System Schematic and Bill of Materials
10. Software

Subtask 5.2 - Detailed Enclosure Design

Under this subtask, Omnion shall design the prototype packaging to incorporate the new core module. The packaging shall be designed for minimum manufacturing cost and maximum product reliability. The result of this subtask shall be a design for the PCS enclosure.

Subtask 5.3 - Interact with Vendors to Optimize Component Selection/Specifications

Omnion's engineering and procurement personnel shall meet with prospective vendors to explore alternatives to minimize cost while enhancing reliability. Consideration shall be given to certification laboratory requirements to ensure compliance of both the components and the overall design. The result of this subtask shall be a list of potential vendors. Major components of the PCS are listed below:

1. Inductors
2. Bridges
3. Laminated Bus
4. PC Boards
5. DC & AC Capacitors
6. Disconnects, AC & DC
7. Fuses
8. Terminal Blocks
9. Wire Harness
10. Transformer
11. EMI Filter
12. Miscellaneous

Task 6 - Test Procedures and O&M Manual

Under Task 6 Omnion shall refine product test procedures and draft a comprehensive Operation and Maintenance Manual an integral part of the design process developed under the Sandia Quality Contract #AU-5805A. This will be accomplished in Tasks 6.1 - 6.2. The results of this task shall be a user-friendly O&M manual and full product test procedures incorporating quality control procedures in compliance with ISO 9001 standards.

Subtask 6.1 - Revise and Refine Test Procedures

Omnion shall improve test procedures to ensure comprehensive testing of the product at the least possible labor cost. The prototype test procedures shall be re-written to reflect changes in the design and/or product specification. Where appropriate, new procedures shall be incorporated to better test the product. Where self-test features have been incorporated in the design, the test procedures shall be simplified to minimize testing cost. The results of this subtask shall be test procedures incorporating quality control measures and meeting ISO 9001 standards for the following boards and systems:

1. Master Control
2. Analog Interface
3. Digital I/O Interface
4. Regulator

5. System/Prototype Data/Temp Qualification

Subtask 6.2 - Draft O&M Manual

Omnion shall prepare a "convenient-to-use" O&M Manual which covers safety considerations, shipping, installation, operation and troubleshooting of the product. Graphics shall be used wherever possible to minimize the amount of text required to communicate with the user. The result of this subtask shall be a user friendly O&M Manual for the product.

Task 7- Manufacturing Development

Under task 7, OMNION will design and develop the manufacturing Process for the product, including development of suitable jigs and fixtures for assembly and test. This will be accomplished in Tasks 7.1 - 7.5. The results of this task will be a documented manufacturing process, including functional supporting manufacturing equipment.

Subtask 7.1 - Design & Document Manufacturing Process

Omnion will provide a written description of the revised manufacturing process with supporting shop floor drawings to show material flow and processing stations. In addition, Omnion shall provide 35mm quality photos illustrating the production process. Omnion will prepare a document with pictures and text that describe each step of the assembly operation and quality control checks along the way. The result of this subtask shall be a manufacturing process manual for the 3300.

Subtask 7.2 - Design and Document Manufacturing Tools, Jigs, and Fixtures

Omnion shall design the tools, jigs and fixtures required to implement the manufacturing process developed in Subtask 7.1 above. Omnion engineering and production personnel shall design the equipment necessary for the production of the PCS. These designs will minimize manufacturing cost while ensuring product quality.

Subtask 7.3 - Design and Document Test Fixtures

Omnion shall design the necessary test fixtures to facilitate the manufacturing process developed in subtask 7.1 above. Omnion engineering and test personnel shall work together to design the test fixtures needed to complement the manufacturing process. Test fixtures shall be designed to accommodate verification of control functions through dedicated software routines wherever possible. Omnion shall provide designs and specifications for test fixtures capable of comprehensively testing the product with minimum labor content. Omnion has already designed test fixtures for testing other boards and this task will be used to modify existing PCB test fixtures to test the 3300 boards, and to design of any other test fixtures required.

Subtask 7.4 - Evaluation of Manufacturing and Test Equipment

After Omnion has put in place the equipment necessary to manufacture the PCS as called for in subtasks 7.2 and 7.3, Omnion shall conduct preliminary testing to determine the feasibility and accuracy of this equipment.

Subtask 7.5 - Qualify and Select Component Vendors

Omnion shall determine preferred and alternate vendors for all major PCS components by qualifying and ranking vendors based on their ability to supply the required components, their ability to make timely deliveries, quality, price, terms and soundness of operations. Omnion shall review track records with respect to price, quality, and delivery for those vendors with which Omnion has experience. Omnion shall perform an onsite audit of proposed new vendors where practical. The result of this subtask shall be the selection of the approved components for the PCS.

Task 8 - Fabricate and Test Preproduction Model

After Omnion completes assembly of the prototype Series 3300, Omnion shall undertake engineering assessment, testing and evaluate the performance of the test pre-production unit to verify the design of both the product and the manufacturing process. This will be accomplished in Tasks 8.1 - 8.3. The results of this task shall be verification that the 100-kilowatt, three-phase PCS Series 3300 meets or exceeds specifications, and evaluation of the suitability of the redesigned manufacturing process for the new unit. Omnion shall also submit applications for listing/certification for UL and FCC testing.

Subtask 8.1 - Test Preproduction Unit

Omnion shall perform functional and characterization testing on the preproduction model. Testing shall also be performed on the test equipment fabricated in subtask 7.4 above. The result shall be a report summarizing the performance of the prototype to specifications and an assessment of the manufacturing line, including ease of operation.

Subtask 8.2 - UL and FCC Test/Evaluation, Listing/ Certification

Omnion shall complete the necessary paperwork and submit the Series 3300 for UL listing and FCC acceptance.

Subtask 8.3 - Optimize Preproduction Model and Manufacturing Equipment

Omnion shall identify and engineer any design improvements identified as a result of the of the preproduction model and/or manufacturing equipment burn-in testing and evaluation. The results shall be a production PCS design and a manufacturing line demonstrating the capability to produce the Series 3300 to design specifications.

Task 9 - Presentations and Publications

Subtask 9.1 - Present Work at NCPV Conference

Omnion shall prepare presentation and attend the 1998 NCPV Conference to inform program participants of the project progress.

Subtask 9.2 - Conduct Semi-Annual Progress Reviews

Omnion shall prepare presentations for semi-annual reviews to be held at Omnion's facilities to inform sponsors of the project progress.

Task 10 - Project Management and Reporting

Subtask 10.1 - Monthly Technical Status Reports

Omnion shall prepare and submit monthly technical status reports.

Subtask 10.2 - Annual Executive Technical Progress Summary

Omnion shall prepare and submit annual executive technical progress summaries.

Subtask 10.3 - Annual Technical Progress Report

Omnion shall prepare and submit annual technical progress reports.

Subtask 10.4 - Final Technical Report

Omnion shall prepare and submit a final technical report.

Subtask 10.5 - Quarterly Cost Plans

Omnion shall prepare and submit quarterly cost plans.

Subtask 10.6 - Subcontract Management Summary Report

Omnion shall prepare and submit a subcontract management summary report.

Subtask 10.7 - Small Business and Disadvantaged Business Plan Reports

Omnion shall prepare and submit small business and disadvantaged business subcontracting plan reports.

Subtask 10.8 - Provide Overall Contract and Technical Project Management

Omnion shall provide overall contract and technical project management to ensure a successful development.

Appendix B - Project Schedule/Milestones/Deliverables

Project Schedule

The scope of work defined for the project award was organized into several tasks with timelines for delivery established. See project schedule summary in Table B-1 below. A detailed project schedule, Table B-2, was developed in conjunction with a project schedule Gantt Chart and used as a project management tool for tracking and reporting on the project's progress. The scope of work was changed when the Technical Monitoring Team realized the constraints that the soft-switching technology selected for the 3400 presented in meeting PvMaT goals. The model number was changed to 3300 to reflect the change from 3400 soft-switching technology to hard-switching technology.

Task	Description	Start Date	Finish Date
1.0	Specification Development	04/21/96	04/15/97
2.0	Prototype Design and Fabrication	09/01/96	04/29/97
3.0	Customer/User Demonstration and Review	04/16/97	05/05/97
4.0	3400 Preproduction PCS Development	05/05/97	06/19/97
5.0	Test Procedures and O&M Manual	06/19/97	07/18/97
6.0	Manufacturing Development	07/18/97	11/24/97
7.0	Fabricate and Test Pre-Production Model	11/24/97	2/26/98
8.0	Presentations and Publications	05/19/97	05/19/98
9.0	Project Management and Reporting	12/21/95	05/19/98
	Technology Transition: 3400 Soft-Switching Technology to 3300 Hard-Switching Technology	12/15/97	03/10/98
4.0	3300 Pre-Production PCS Development	05/05/97	06/19/97
5.0	Pre-Production PCS Develópement	01/02/98	02/05/98

Table B-1: PVMaT - Series 3300/3400 Project Schedule Summary

Task	Description	Start Date	Finish Date
6.0	Test Procedures and O&M	02/05/98	03/10/98
7.0	Manufacturing Developement	02/23/98	06/22/98
8.0	Fabricate and Test Pre-Production and Production	03/02/98	06/30/98

Table B-1: PVMaT - Series 3300/3400 Project Schedule Summary

Milestones

The PVMaT - Series 3300 project milestones are divided into Phase I and Phase II milestones to correspond to the two phases of the development effort and contract. OMNION performed tasks 1 through 10 as described in Section 2 of this report to meet the following specific project milestones:

Phase I

m-1.1.2.a Initiated lower-tier subcontract with soft-switching core module vendor SST

m-1.1.3.a Completed resonant power module specification in conjunction with SST

m-1.1.1 Completed development of draft product specifications (subtask 1.1)

m-1.1.2 Completed Failure Modes and Effects Analysis (FMEA) of all OMNION 3-phase IGBT power conversion systems deployed since 1990 (subtask 1.2)

m-1.1.3 Completed customer review and comment on draft specifications with eight customers (subtask 1.3)

m-1.1.6 Completed draft final working product specifications (subtask 1.6)

m-1.1.8 Completed Task 1 - Specification Development

m-1.2.7.a Demonstrated soft-switching core module high power operation at SST

m-1.3.1.a Completed deployment of soft-switching core module at SST (subtask 2.1)

m-1.3.2.a Completed prototype soft-switching power conversion system design (subtask 2.2)

m-1.2.3 Completed prototype soft-switching power conversion system packaging (subtask 2.3)

m-1.3.4.a Completed final bill of material and component specifications for prototype soft-switching power conversion system (subtask 2.4)

m-1.3.5.a Completed assembly of 100-kW, 3-phase, soft-switching power conversion system prototype (subtask 2.7)

m-1.4.2 Completed 100-kW, 3-phase, soft-switching power conversion system prototype demonstration to customer/user group (subtask 3.1)

m-1.2.5 Completed development of test procedures for the 100-kW, 3-phase, soft-switching power conversion system
(subtask 2.6)

Phase II

m-1.4.1 Completed updating of design documentation to "as-tested" status (subtask 2.9)

m-1.4.3 Completed review and finalized preproduction product specifications (subtask 3.2)

m-1.4.4 Completed Task 2 - Prototype Design and Fabrication

m-1.4.5 Completed Task 3 - Customer/User Demonstration and Review

m-1.2.4 Completed Failure Modes and Effects Analysis (DFMEA) of the prototype 100-kW, 3-phase, soft-switching power conversion system Design (subtask 2.5)

m-1.3.2 Completed prototype 100-kW, 3-phase, soft-switching power conversion system testing (subtask 2.8)

m-2.1.1 Completed comparison between OMNION's model 3200 and 3400 3-phase, 100-kW power conversion system design
(subtask 4.1)

m-1.4.7 Completed Task 4 - 3400 Preproduction Power Conditioning System Development

m-2.5.1 Complete revision of the PCS prototype design to incorporate the Skiipack hard-switched technology (subtask 5.1)

m-2.6.2 Completed revision of Operation and Maintenance (O&M) Manual for production of 100-kW, 3-phase, power conversion system product (subtask 5.3)

m-2.5.2 Completed redesign of the prototype packaging for the new core module (subtask 5.2)

m-2.5.3 Completed Task 5 - Development of Revised and Repackaged Design for the 3300, incorporating improved hardswitched esign to Meet the Defined Performance Improvements

m-2.6.1 Completed revision of test procedures incorporating quality control steps to ISO 9001 standards. The quality control steps are part of the design phase process developed under the Sandia Quality Contract #AU-5805A(subtask 6.1)

m-2.7.1 Completed redesign of manufacturing tools, jigs, and fixtures for the Series 3300 PCS (subtask 7.2, 7.3)

m-2.7.2 Completed preliminary evaluation of the manufacturing equipment (subtask 7.4)

m-2.8.3 Completed optimization of the manufacturing process and Series 3300 for production (subtask 8.3)

m-2.8.2 Completed submission of Series 3300 to UL and FCC for evaluation (subtask 8.2)

m-2.8.1 Demonstrated the Series 3300 perform to specifications (subtask 8.1)

m-2.8.4 Completed Task 8 - Demonstration of the Series 3300 for the Technical Monitoring Team m-2.8.5 Completed Tasks 4, 5, 6, 7, and 8

Phase III

m-3.1.1 Initiate discussions with UL to review listing requirements. (Subtask 9.4)

m-3.1.2 Complete review and definition of modifications to the prototype PCS 3300. (Task 9.1)

m-3.1.3 Complete review of production line (manufacturing tools, jigs and fixtures) for the Rev. 1 PCS 3300. (Task 9.2)

m-3.1.4 Complete redesign/modifications to production line (manufacturing tools, jigs and fixtures) for the Rev. 1 PCS 3300. (Subtask 9.2)

m-3.2.1 Complete fabrication of Rev. 1. (Subtask 9.2)

m-3.2.2 Complete functional and characterization testing of Rev. 1. (Subtask 9.3)

m-3.2.3 Complete submission of Rev.1 PCS 3300 to UL listing. (Subtask 9.4)

m-3.2.4 Complete modifications to the PCS 3300 manufacturing line as indicated by the Rev. 1 experience and the UL listing process. (Subtask 9.5)

Deliverables

The PVMaT - Series 3300 project deliverables are divided into Phase I and Phase II deliverables to correspond to the two one-year phases of the subcontract. OMNION furnished the following Phase I and Phase II deliverables as part of this subcontract:

Phase I

D-1.1 Summary report of Omnion's PCS field failure experience (subtask 1.3)

D-1.2 Final draft of the product specifications (subtask 1.6)

D-1.8 SST delivers soft-switching PCS core module to Omnion

D-1.4 Final bill of material and component specifications for the prototype PCS design (subtask 2.4)

D-1.3 Sample of the PCS prototype system packaging (subtask 2.3)

D-1.7 Preproduction product specifications (subtask 3.2)

Phase II

D-1.5 Detailed definition and plan for testing procedures (subtask 2.6)

D-1.6 Informal report listing engineering design modifications (subtask 2.9)

D-2.1 Deliver illustrated drawing of revised and repackaged PCS design (Task 4, 5)

D-2.2 Deliver outline of revised test procedures (subtask 6.1)

D-2.3 Deliver draft PCS 3300 O&M Manual (subtask 6.2)

D-2.4 Deliver illustrated drawings or general schematics of designs for tools, jigs, and test fixtures (subtask 7.2, 7.3)

D-2.4a Deliver lessons-learned report summarizing results of discontinued development of the Series 3400 PCS

D-2.5 Deliver test results of preproduction 100-kW 3-phase Series 3300 PCS (subtask 8.1, 8.2)

D-2.6 Deliver summary report detailing assessment results of preproduction model and manufacturing equipment performance (subtask 8.3)

D-2.7 Deliver diagrams or illustrations of the manufacturing process with supporting shop floor drawings, material flow, and process stations (subtask 7.1)

Detailed Project Schedule

A detailed project schedule is presented in Table B-2 below. A description of the work performed under the detailed project tasks can be found in the previous section, Section 2, of this report.

Task	Description	Hours	Start Date	Finish Date
	PVMAT	**4012**	**12/21/95**	**5/19/98**
	CONTRACT AWARD	**0**	**12/21/95**	**12/21/96**
1.0	**Specification Development**	**418**	**4/21/96**	**4/15/97**
1.1	Draft Product Specification	60	4/21/96	4/21/96
1.2	Analyze Field Failures	120	6/27/96	6/27/96
1.3	Present Product Specification with Key Customers/Users	160	2/7/97	2/7/97
1.4	Present Product Specification with IEEE	24	2/7/97	2/7/97
1.5	Present Product Specification with UL recognition.	20	2/7/97	2/7/97
1.6	Draft Final Working Product Specification			
2.0	**Prototype Design and Fabrication**	**1509.5**	**9/1/96**	**4/29/97**
2.1	Develop Core Resonant Converter	148.5	2/10/97	2/10/97
2.2	Design Prototype Power Conversion System	367	9/1/96	4/29/97
2.2.1	Master Control Board	80	9/1/96	9/1/96
2.2.2	Analog Board	78.5	9/1/96	9/1/96

Table B-2: PVMaT - Series 3300 Project Schedule

Task	Description	Hours	Start Date	Finish Date
2.2.3	System BOM/Schematics	140.5	12/1/96	12/1/96
2.2.4	Software	60	1/21/97	1/21/97
2.2.5	System State Design	8	1/21/97	1/21/97
2.3	Design Prototype System Packaging	308	1/21/97	1/21/97
2.4	Interact with Vendors to Optimize Component Selection/Specifications	20	2/7/97	2/7/97
2.5	Conduct Failure Modes and Effects Analysis	60	4/15/97	4/29/97
2.6	Develop PCS Test Procedures	96	2/7/97	2/7/97
2.6.1	Master Control Board Test Procedure	16	2/7/97	2/7/97
2.6.2	Analog Interface Board Test Procedure	16	2/7/97	2/7/97
2.6.3	Core Module Test Procedure	16	2/7/97	2/7/97
2.6.4	System Test Procedure	48	2/7/97	2/7/97
2.7	Assemble PCS Prototype	130	2/10/97	2/10/97
2.8	Test PCS Prototype	336	2/7/97	3/28/97
2.8.1	Test Master Control Board	40	2/7/97	2/7/97
2.8.2	Test Analog Interface Board	16	2/7/97	2/7/97
2.8.3	Test Core Module	40	2/10/97	2/10/97
2.8.4	Test System	240	3/17/97	3/28/97
2.9	Prepare Design Documentation	44	4/21/97	4/29/97
3.0	**Customer/User Demonstration and Review**	**120**	**4/16/97**	**5/5/97**
3.1	Demonstrate Prototype to Customer/User Group	68	4/16/97	4/21/97
3.2	Review and Finalize Product Specification	52	4/29/97	5/5/97
4.0	**3400 PreProduction PCS Development**	**814**	**5/5/97**	**6/19/97**
4.1	Finalize Pre-Production Model Schematics/ Component Specifications	508	5/5/97	6/12/97
4.2	Finalize Pre-Production Model Packaging	184	5/5/97	5/19/97

Table B-2: PVMaT - Series 3300 Project Schedule

Task	Description	Hours	Start Date	Finish Date
4.3	Interact with Vendors to Optimize Components	122	6/12/97	6/19/97
6.0	**Test Procedures and O&M Manual**	**115**	**6/19/97**	**7/18/97**
6.1	Revise and Refine Test Procedures	75	6/19/97	6/23/97
6.2	Draft Operation & Maintenance Manual	40	6/23/97	7/18/97
7.0	**Manufacturing Development**	**320**	**7/18/97**	**11/24/97**
7.1	Design and Document Manufacturing Process	160	7/18/97	8/5/97
7.2	Design and Document Manufacturing Tools, Jigs, Fixtures	80	8/5/97	8/20/97
7.3	Design and Document Test Fixtures	16	8/20/97	10/21/97
7.4	Evaluation of Manufacturing & Test Equipment	24	10/21/97	11/24/97
7.5	Qualify and Select Components	40	10/21/97	10/28/97
8.0	**Fabricate and Test Pre-Production Model**	**1116**	**11/24/97**	**2/26/98**
8.1	Fabricate Preproduction Model	276	11/24/97	11/28/97
8.2	Test Preproduction Model	300	11/28/97	12/10/97
8.3	UL Test/Evaluation	184	12/10/97	12/23/97
8.4	EMI Test Evaluation	160	12/23/97	1/1/98
8.5	Modify Preproduction Model and/or Manufacturing Equipment	60	1/1/98	1/6/98
8.6	Submit Unit for UL listing Certification	52	12/25/97	1/28/98
8.7	Conduct Witness Testing	84	1/6/98	1/14/98
	Transition from 3400 Soft-Switching Technology to 3300 Hard-Switching Technology		**12/15/98**	**3/10/98**
9.0	**Presentations and Publications**	**300**	**5/19/97**	**5/19/98**
9.1	Present Work at NCPV Conference	60	2/2/98	5/19/98
9.2	Conduct Semi-Annual Progress Reviews	240	5/19/97	5/19/98

Table B-2: PVMaT - Series 3300 Project Schedule

Task	Description	Hours	Start Date	Finish Date
10.0	**Project Management and Reporting**	**412**	**12/21/95**	**5/19/98**
10.1	Prepare Monthly Technical Status Reports	100	5/17/96	5/19/98
10.2	Prepare Annual Executive Technical Progress Summaries	16	5/19/97	5/19/98
10.3	Prepare Annual Technical Progress Reports	60	5/19/97	5/19/98
10.4	Prepare Final Technical Report	80	5/19/98	5/19/98
10.5	Prepare Quarterly Cost Plans	16	12/21/95	12/21/95
10.6	Prepare Subcontract Management Summary Report	0	12/21/95	12/21/95
10.7	Prepare Small Business & Disadvantaged Business Plan Reports	0	12/21/95	12/21/95
10.8	Provide Overall Contract and Technical Project Management	140	5/19/98	5/19/98

Table B-2: PVMaT - Series 3300 Project Schedule

Appendix C - Proposed Series 3400 Specification

1.0 Performance Analysis

- 1.1 Standby Losses: Less than 40 Watts, excluding the transformer.
- 1.2 Peak Efficiency: 95%, maximum in the area of 40-80% power for the base unit only. Addition of an optional transformer will reduce this by 3-5%.
- 1.3 Audible Noise: 60 dBa or less at 2 meters, excluding the transformer.
- 1.4 Power Factor when operating over 20kW: >0.95
- 1.5 Current THD when operating over 20kW: <5%

2.0 Functionality Analysis

- 2.1 Array Input
  - 2.1.1 Nominal Operating Voltage: 420 VDC
  - 2.1.2 Two Wire Input, Negative input grounded by the inverter
  - 2.1.3 Maximum Power Tracking Voltage: 200*-600 VDC
  - 2.1.4 Maximum Open Circuit Voltage: 600 VDC
  - 2.1.5 Maximum Operating Current: 350 ADC
  - 2.1.6 Maximum Ripple Voltage: 2% RMS from 30% to 100% of rated output.
- 2.2 Utility Output
  - 2.2.1 Nominal Operating Voltage: 480 VAC ± 10%
  - 2.2.2 Maximum Operating Current: 130 AAC
  - 2.2.3 Nominal Output Power: 100 kW
  - 2.2.4 No Load Voltage: 440-508 VAC (ANSI C84.1-1995 Range B)
  - 2.2.5 Operating Voltage: 432-528 VAC
  - 2.2.6 Nominal Operating Frequency: 60 Hz
  - 2.2.7 Optional Operating Frequency: 50 Hz
  - 2.2.8 Operating frequency range: 59-61Hz (49-51Hz) [factory programmable from 45 to 65Hz]

*Note: Input voltage less than 300 VDC will result in power rating reduction. The input to the PCS is current limited to 350 ADC.

3.0 Agency Requirements/Analysis

- 3.1 UL 1741

4.0 Conformance to Standards

- 4.1 NEC 1996

4.2 FCC Part 15A, and Part 15B radiated and conducted

4.3 IEEE P929 Draft 3 November 3, 1997

4.4 IEEE 519-1992

5.0 User Interface

5.1 DC Disconnect Switch – A DC disconnect switch may be supplied to isolate the PCS converter from the PV array for servicing purposes. The disconnect switch shall be capable of being padlocked and shall contain visible break contacts. The disconnect shall be mounted externally on the PCS enclosure.

5.2 AC Disconnect Switch - An AC disconnect switch may be supplied to isolate the PCS converter and transformer from the utility service. The disconnect switch shall be capable of being padlocked and shall contain visible break contacts. The AC disconnect shall be mounted externally on the PCS enclosure.

5.3 LCD – A 2 line by 16 character display will be used to show system operating and status information. The first line will show the mode and if running the power level. The second line will show fault information if any and when running it will show DC voltage and total kW hours.

5.4 RS232 Interface - PCS operational status and remote customer interfacing can be accomplished over an isolated RS232 interface.

5.5 Hand Held Pendant – As an option, Omnion can supply a hand held pendant that allows field programming of over and under voltage and frequency set points as well as DC ground fault set points.

5.6 DC Ground Fault Detection and Interruption - The PCS will alarm and go to the Standby/Fault Mode upon detection of excessive PV array ground current. The trip level is field adjustable in the range of 2 to 10 ADC via the RS232 interface. The PCS shall contain a means of interrupting the ground fault current through the disconnection of the known ground.

5.7 PV String Current Monitoring - Current monitoring of a single PV string will provide the customer with additional information on string and array performance. This information will be made available via the RS232 interface.

5.8 PV String Power Monitoring - Power monitoring of the PV input will provide the customer with additional information on the PV input performance. This information will be made available via the RS232 interface.

5.9 DC Combiner Section- A DC Combiner Section may be added to the DC disconnect switch option above to accommodate multiple monopole source circuit inputs. The Combiner Section shall provide accommodation for terminating up to ten source circuits and include fusing on up to ten positive inputs.

5.10 A convenience receptacle may be supplied and be rated 15 amps, 120VAC

5.11 A backup protective function system may be provided for redundant monitoring for O/U voltage and frequency on the AC line and will have the capability of being field adjustable.

5.12 The PCS may be provided with the necessary space (H x W x D) for insertion of revenue metering equipment. This area will be physically isolated from all other areas of the PCS. Revenue meter equipment to be supplied and installed by customer.

5.13 Customer contact closure control

Status:
-PCS Fault/Shutdown
-PCS On

Control:
-PCS Disable

5.14 A separate outdoor pad mounted, dry-type isolation transformer shall be supplied to match the converter output voltage to the utility voltage. A +5% and -5% voltage tap will be provided on the primary winding of the transformer. The transformer output parameters shall be:

Operating Voltage: 480 VAC ±10%
Output Winding: Delta
Number of Phases: Three
Frequency: 60 Hz
Nominal Operating Current: 120 AAC
Maximum Operating Current: 130 AAC

The transformer shall be supplied loose for installation by others.

5.15 The PCS shall be provided with dedicated termination points for the HV and LV terminations of the transformer defined in 4.1.4 above, as well as dedicated termination points for the utility grid interconnection(480VAC version).

6.0 Reliability, Uptime, and Design Life

6.1 Warranty

6.1.1 Omnion Power Engineering Corporation warrants the proposed equipment for a period of one (1) years from date of shipment against defects of materials or workmanship, exclusive of damages or abuse outside of Omnion's control.

6.2 HALT Tested: Yes

6.3 Design Life: Design mean time between failure is 60,000 hours.

7.0 Service and Installation

7.1 Training: Training for installation and service is available. Contact the factory for details.

7.2 Installation Procedures: Included as part of the O&M Manual with each system. Installation is the responsibility of the customer. Omnion will provide the customer with equipment drawings showing cable entrance areas. An interconnect drawing will be provided showing voltage and current requirement of all interconnect cabling.

8.0 Modularity and Expandability

8.1 Multiple units may exist on a site. Each unit requires that the input DC be grounded and that the output AC goes through an isolation transformer. If multiple PCS are connected to the same array, the factory must be made aware of the application to modify the control to allow proper power tracking of the input power.

9.0 Size, Weight and Transportation

9.1 Dimensions: 60" high, 60" wide, and 24" deep.

9.2 Weight: 600 lb. Approx.

9.3 Transportation: Truck.

10.0 Operating Environment

10.1 Temperature: -30×C to 55×C (-22×F to 122×F)

10.2 Humidity: 0 to 100% including rain and snow

11.0 System Architecture

11.1 The PCS converter shall be self-commutated utilizing insulated gate bipolar transistors.

12.0 Development Platform

12.1 IGBT Power Devices

12.2 Intel/Phillips 8051 Microprocessor

13.0 Preliminary Cost

13.1 Design Goal is $25,000 per unit direct costs for labor and material in quantity 100 batches for the base unit.

14.0 Strategic Suppliers Defined

14.1 Manutronics for PCB assemblies

14.2 Heat sink supplier

14.3 Microprocessor

15.0 Model Number Definition: Omnion Series 3400.

16.0 Protective Features

16.1 The PCS shall include appropriate self-protective and self-diagnostic features to protect itself and the PV array from damage in the event of PCS component failure or from parameters beyond the PCS's safe operating range due to internal or external causes. The self-protective features shall not allow signals from the PCS front panel or from remote customer inputs to cause the PCS to be operated in a manner which may be unsafe or damaging.

16.2 The PCS when operating in parallel with the utility service shall be capable of interrupting line-to-line fault currents and line-to-ground fault currents. Faults due to malfunctions within the PCS shall be cleared by the PCS protective devices and not by the site utility service protection device.

16.3 The PCS control shall incorporate Omnion's standard Utility Protection. The PCS shall go to the standby/fault mode anytime the utility voltage exceeds +10% of nominal for 0.2 seconds or -10% of nominal for 2 seconds (factory set points). The over/under voltage set points and time delays shall be field adjustable via the use of the optional pendant controller and the RS232 port. Up to two sets of values for each parameter may be programmed.

16.4 The PCS control shall incorporate Omnion's standard Utility Protection. The PCS shall go to the standby/fault mode anytime the frequency exceeds 61 Hz or falls below 59 Hz for 0.2 seconds (factory set points). The over/under frequency set points and time delays shall be field adjustable via the use of the optional pendant controller and the RS232 port. Up to two sets of values for each parameter may be programmed.

16.5 Temperature sensors shall be incorporated in the power bridge within the PCS. The PCS shall alarm and go to Shutdown when an over-temperature condition is detected. (This fault condition is a lockout mode fault.)

16.6 An early warning power bridge over-temperature signal is used to drop the PCS output power to 75% of rated.

16.7 The PCS shall alarm and go to Standby/Fault in the event of a bridge fault condition.

16.8 The PCS shall alarm and go to Standby/Fault in the event synchronization is not achieved. PCS shall attempt to synchronize continuously.

16.9 The PCS shall have provisions for prevention of reverse power flow.

16.10 (Optional) The PCS shall go to the Standby/Fault mode upon detection of a DC ground fault level of 2 ADC as a factory default setting.

16.11 (Optional) An optional hand held pendant shall have the capability of being used to program the following protective function set points.

-AC O/U Voltage Magnitude
-AC O/U Voltage Time Delay
-AC O/U Frequency Magnitude
-AC O/U Frequency Time Delay
-DC Ground Fault action (shutdown, Standby/Fault, Run)
-DC Ground Fault Magnitude
-DC Ground Fault Time Delay

17.0 Packaging Requirements

17.1 Enclosure

17.1.1 Free standing

17.1.2 NEMA 3R

17.1.3 Inverter is not user accessible

17.1.4 Painted Steel

17.1.5 Holes for ½ inch conduit will be provided for both the AC and DC electrical connections. Space will be provided for increasing to ¾" conduit.

17.1.6 Segregated compartment for AC and DC interconnect, input and output fusing, and input and output surge protection will be provided.

17.1.7 Passive air cooled

Appendix D - Three Phase UI/PV PCS Specification Comparison

Ref	Description	3400	SMUD	Team-up	Amoco Enron	2400
1.1	National Electrical Code	S	S	S	S	S
	National Electrical Safety Code	S	S	S	S	S
	IEEE 928-1986	S	S	S	S	S
	IEEE 929-1988	S	S	S	S	S
	IEEE 519-1992	S	S	S	S	S
	ANSI/IEEE C37-1986	S	S	-	S	S
	ANSI/IEEE C57-1986	S	S	-	S	S
	ANSI/IEEE C37, 90	S	S	-	S	S
	FCC Part 15, Subpart A, Subpart B	S	S	S	S	S
	Insulated Cable Engineers Assoc. Standards (ICEA)	-	S	S	-	-
	UBC - Uniform Build Code 1995 (Seismic Loads)	-	S	S	S	-
	NEMA 3 or Equiv. for Outdoor Enclosures	-	S	S	S	-
	OSHA Directives	-	S	S	S	-
	ANSI/ASCE 7-88	-	S	S	S	-
	UL, ETL	S	-	S	-	S
	Local Codes & Standards	-	S	S	-	-
	IEC Standards	-	-	-	S	-
	ISO Standards	-	-	-	S	-
	NFPA Standards	-	-	-	S	-

S = Standard **O = Optional** **BB = BaseBall Fault (3 strikes=lockout)**

Ref	Description	3400	SMUD	Team-up	Amoco Enron	2400
2.1.1	Temperature Range -Operating	-20 to 131°F	18 to 111°F	-	28 to 122°F	-5 to 115°F
	Temperature Range -Storage	-40 to 150°F	-	-	-	-
2.1.2	Humidity	0 to 100%	0 to 100%	-	27 to 84%	0 to 100%
3.1	DC Interface	2 Wire	2 or 3 Wire	2 or 3 Wire	?	3 Wire
	Grounding	Neg Leg	Neut or Neg Leg	Neut or Neg Leg	?	Neut Leg
3.2	Input Voltage	200-600 Vdc	600 Vdc Max	600 Vdc Max	?	360-600 Vdc
	Input Current	0-350 Adc	500 A Max	500 A Max	?	0-18 Adc
	Max Ripple	2% RMS	-	-	?	3.5% RMS
4.1.1	Nominal Output	100 kVA	-	-	-	6 kVA
	Nominal Output Voltage	400 Vac	Not Spec'd	Not Spec'd	Not Spec'd	120 Vac
	Voltage Tolerance	±10%	±10%	+6, -14%	±5%	±10%
	Frequency Tolerance	+1, -1.5 Hz Programmable (Opt.)	+1, -1.5 Hz	+1, -1.5 Hz	+1.5, -2.9 Hz (50 Hz)	+1, -1.5 Hz
	Max Operating Current	145 Aac	-	-	-	-
4.1.3	PCS Enclosure Outdoor	Outdoor /Wall /Pad	Outdoor	Outdoor	Outdoor	Outdoor

S = Standard **O = Optional** **BB = BaseBall Fault (3 strikes=lockout)**

Ref	Description	3400	SMUD	Team-up	Amoco Enron	2400
4.1.4	DC Disconnect	O	S	S	S	-
	Load Break	O	O	O	O	-
	Visible Break	S	S	S	S	-
	Lockable	O	O	O	S	-
	Non-Load Break (Quick Connect)	S				
4.1.5	AC Disconnect	O	S	S	O	-
	Fused	O	O	O	O	-
	Breaker	O	O	O	S	-
	Load Break	O	O	O	S	-
	Visible Break	S	S	S	S	-
	Lockable	O	S	S	S	-
	Non-Load Break (Quick Connect)	S				
4.1.6	Output Transformer					
	Enclosure	Outdoor /Pad	Outdoor	Outdoor	Outdoor	-
	Output Voltage	480 Vac	Match Utility	?	12.47kV	-
	Output Winding	Delta	-	?	Delta	-
	Max Current	130 Aac	-	?	-	-
4.2.2a	Shut Down					
	Remote Disable	S (RS232)	S	S	-	-
	Emergency Stop	-	S	S	S	-
	Lockout Mode Fault	-	S	S	-	S
4.2.2b	Standby/Fault (Auto Restart)	#Time				

S = Standard **O = Optional** **BB = BaseBall Fault (3 strikes=lockout)**

Ref	Description	3400	SMUD	Team-up	Amoco Enron	2400
	Over-Temperature	S (BB)	-	-	-	S
	DC Ground Fault	O (BB)	-	-	-	S (BB)
	Bridge Fault	S (BB)	-	-	-	S (BB)
	Logic Power	O (BB)	-	-	S	S (BB)
	Synchronization	S (BB)	S	S	S	S
	O/U Voltage	S (BB)	S	S	S	S
	O/U Frequency	S (BB)	S	S	S	S
	Loss of Utility	S (BB)	S	S	-	S
4.2.2c	Standby/Ready					
	Insufficient Solar	S	S	S	S	S
4.2.2d	Run	S	S	S	S	S
4.3.1	Fail Safe	S	S	S	S	S
4.3.2	Fault Clearing	S	S	S	S	S
4.3.3	O/U Voltage	+10%/ 0.5s	+6%	+6%	±5%	±10%
	Field Adjustable	S (2setpts) via Pendant/ RS232 (Opt.)	S	S	S	S
4.3.4	O/U Frequency	61 Hz/ 0.25s, 58.5 Hz/ 2s	61 Hz/ 0.25s, 58.5 Hz/ 2s	61 Hz/ 0.25s, 58.5 Hz/ 2s	51.5 Hz, 47.1 Hz	61 Hz, 58.5 Hz
	Field Adjustable	S (2setpts) via Pendant/ RS232 (Opt.)	S	S	S	S

S = Standard **O = Optional** **BB = BaseBall Fault (3 strikes=lockout)**

Ref	Description	3400	SMUD	Team-up	Amoco Enron	2400
4.3.5	Over Temperature	Bridge	Bridge	Bridge	-	Bridge
4.3.6	Over Temperature	75% Derate	Shut-down	Shut-down	-	Shut-down
4.3.7	Bridge Fault	S	-	-	-	S
4.3.8	Loss of Synchronization	S	S	S	S	S
4.4.1	LCD Display	O RS232/ Pendant				
	AC kW	S	S	?	?	S
	VDC	S	S	?	?	S
	Mode	S	S	?	?	S
	Bridge Fault	S	S	?	?	S
	Sync Error	S	S	?	?	S
	Utility Out-of-Tolerance	S	O	?	?	S
	Over Temp	S	S	?	?	S
	Ground Fault	O	S	?	?	S
4.4.2	Controls					
	Emergency Stop	S	-	S	S	-
	Reset	S	S	S	S	S
	On/Off	S	S	S	S	S
	Man/Auto (Const. Volt)	O	-	-	-	-
	Remote Disable	S	-	-	-	S
4.4.4	Maximum Power Tracking	S	S	S	S	S
	Anti-Islanding Protection	S	S	S	-	S
	Audible Noise		S	S		S
4.4.5	Remote Control (RS232)					
	Disable	S	S	S	S	-

S = Standard **O = Optional** **BB = BaseBall Fault (3 strikes=lockout)**

Ref	Description	3400	SMUD	Team-up	Amoco Enron	2400
	Reset	S	S	S	S	S
	Local Disable	S	S	S	S	-
	ON/OFF	S	-	-	-	S
4.5.1	Tare Losses (Standby/Shutdown)					
	PCS	40 W	-	-	-	<15 W
	480V Transformer	0	-	-	-	-
	12kV Transformer	?	-	-	-	-
4.5.2	Efficiency (PCS & Transformer)					
	25	90%	?	?	>92%	95.3%
	50	94%	?	?	>92%	95.9%
	75	95%	?	?	>95%	95.5%
	100	95%	?	?	>95%	95.4%
4.5.3	Power Factor	±0.95 >20%	±0.95 >20%	-	0.8 lag - 0.95 lead	±0.95 >20%
4.5.4	Harmonics					
	Current	5%/3% <50th	5%/3%	See IEEE 519-1992	See IEEE 519-1992	<5% >30%
	Voltage	-	5%/1%	-	-	-
4.5.5	FCC Part 15 Sub A/B	S	S	S	S	S
4.6.1	Construction					
	No PVC	S	S	S	-	S
	Class K Stranding	S	S	-	-	S

S = Standard **O = Optional** **BB = BaseBall Fault (3 strikes=lockout)**

Ref	Description	3400	SMUD	Team-up	Amoco Enron	2400
	Flame Retardant (IEEE 383)	S	S	-	S	S
4.6.2	Max Two Leads/Terminal	S	S	-	S	S
4.6.4	Single Point Ground	S	-	-	S	S
4.6.5	20 Yr. Paint	S	S (30 Yr. Paint)	-	30 Yr. Life	S
4.6.6	Outdoor Enclosure	NEMA 3R	S	S	S	S
	Dust Proof	S	S	S	S	S
	Rodent Proof	S	S	S	S	S
	Insect Proof	S	-	-	-	-
	Mount Rails (Pad)	S	-	-	-	-
	Dead Front Access (Ctrl/Pwr)	S	-	-	-	-
4.6.7	Component Identification	S	S	S	S	S
	120 VAC, 20 A Outlet	O	O	-	-	-
4.6.8	PV String Current Monitoring	O	-	-	-	-
4.6.9	PV String Power Monitoring	O	-	-	-	-
4.6.10	DC Combiner	O	-	-	-	-
4.6.11	Backup Protective Functions	O	-	-	-	-
4.6.12	Revenue Metering Compartment	O	-	-	-	-
4.6.13	Time Stamped Events/Storage	-	-	-	-	-
4.6.14	Other Data Logging (Temp/Irr/DC/AC)	-	-	-	-	-

S = Standard **O = Optional** **BB = BaseBall Fault (3 strikes=lockout)**

Ref	Description	3400	SMUD	Team-up	Amoco Enron	2400
4.7.4	DC Ground Fault	O 0/2-10A 0/0,1- 1A	- ? ?	- ? ?	- Fld Adj -	S 0.5A -
6.1	O&M Manual	S	S	S	S	S

S = Standard **O = Optional** **BB = BaseBall Fault (3 strikes=lockout)**

Appendix E - PVMaT/Omnion Series 3400 Customer Review Matrix

Comment Description	Number of Occurrences
ELECTRICAL CONFIGURATION	
1. Optional ADC, kWDC	2
2. Locate control power connection to line side of main fuse	2
3. Add DC blocking diode for prevention of reverse power flow	2
4. Multiple fused source circuit inputs	1
5. PCS output 480 VAC transformerless	3
6. Transformer configuration Wye-Wye	1
7. Contactor between negative and ground (disrupt ground)	1
8. Load break DC disconnecting means	3
9. Load break AC disconnecting means	3
10. Label non-load break disconnect (Do not operate under load) - load break not necessary (AC/DC)	3
11. DC disc open positive only (ground fault protection)	2
12. Add manual control of AC contactor	2
13. Metering socket integral to AC disconnecting means	2
14. Transformer taps if not 480 VAC transformer	1
PROTECTIVE FUNCTIONS	
1. Interrupt and alarm DC ground fault	2
2. Detect DC ground fault no interrupt	1
3. Islanding protection - one second adjustable	1
4. Anti-islanding Protection UL Certified	1
5. DC injection protection	1
6. Protective functions classified as industrial grade	1

Customer Review Matrix

Comment Description	Number of Occurrences
7. Independent detection/backup scheme for islanding protection	1
8. O/U voltage, +6, -14% standard	1
9. O/U frequency, +1, -1.5 Hz standard	1
10. Adjustable setpoints (level, time) - Qty 2 for each parameter with factory default	2
11. Adjustable setpoints - no instantaneous, 1 trip	1
12. No lockout mode faults (equipment/safety only)	3
13. No baseball faults (equipment/safety only)	3
14. Two minute delay on retry	1
15. Five minute delay on retry	1
16. Lockout power fault not necessary	1
17. Three tries and lockout - yes	1
18. Logic power fault not necessary	2
19. Self test scheme	2
PERFORMANCE/OPERATION	
1. Bridge 75% de-rate on over-temperature - yes	2
2. Bridge 75% de-rate on over-temperature not useful	1
3. FCC Part A and Part B vs. just Part B	3
4. FCC 15, Subpart J	1
5. Lower minimum DC operating voltage (300 VDC present)	5
6. Identify power rating at -10% and +10% utility line in spec.	2
7. Audible Noise level 52 dbA or less	1
8. Audible Noise level same as pad mount transformer	1
9. Audible Noise level same as present hard switching	1
LOCAL CONTROL	

Customer Review Matrix

Comment Description	Number of Occurrences
1. On/Off control only (no E-Stop, reset)	4
2. LCD display/Power level indication only	1
3. LCD (MMI) necessary	1
4. LCD remove and pendant substitute	2
5. Local single fault indicator only (no remote DAS)	1
6. Add selector for manual mode (constant voltage)	1
REMOTE COMMUNICATIONS	
1. RS232 local disable via disconnecting	2
2. Modem with RS232 or other - accommodate multiple drops - longer distance - protocol	4
3. Communication multiple units addressing (?RS485)	2
4. Software to support protocol	2
5. Add instrument standard (i.e., SAMI)	1
6. Event storage, time stamped, 5-10 events, 10 cycles prior, 20 cycles after	1
7. DAS built in (kWHr, temp, irradiance, DC/AC voltages/currents, power factor	1
8. Baseball faults, call in diagnostic	1
9. Remote restart	4
10. Remote programmable parameters	1
11. Add auxiliary dry contacts for shutdown	1
12. No dry contact closures	1
13. No remote DAS	1
PACKAGING/ENCLOSURE	
1. Physical Protection - Utility Grade	1

Customer Review Matrix

Comment Description	Number of Occurrences
2. Insect entrance prevention - standard	1
3. Isolate inside air from external (i.e., external heatsink)	2
4. No air conditioners	2
5. Convenience outlet	1
6. No filters	2
7. Strip heater	2
8. No flat bottom for ground mounting	2
9. No user changeable parts	2
10. User interface via dead front control	2
11. Access panel for connections only (RS232, power)	2
12. Access panel for controls	2
13. Space for revenue metering package	1
14. UBC if wall mounted	1
15. NEMA 3R enclosure	1
16. Modularized design (inverter, interconnects, disconnect switch)	1
17. Add storage temperature range to specification	1
18. Make maximum operating temperature 131°F	2
19. Wall mountable	1
MISCELLANEOUS	
1. O&M Manual less than 5 pages (not service manual)	2
2. Timing to market - short	1

Customer Review Matrix

CONTRIBUTORS

Customer	Contact
Ascension Technology	Miles Russell
Florida Power and Light	Joe Chau
PVUSA	Chuck Whitaker
Pacific Gas & Electric	Brian Farmer
UPVG	Steve Hester
SMUD	Dave Collier
Photocomm	Larry Schlueter
Arizona Public Service	Chet Napikoski

Customer/User Group

Appendix F - Series 3300 Specification

This document represents specifications for an Omnion Series 3300 nominal 100 kW utility interconnected power conversion system for use with a photovoltaic array.

1. Codes and Standards
   1.1 Equipment and services supplied shall be controlled to meet the guidelines for engineering design included in the standards and codes listed below. In case of conflict, this specification shall govern.
      1.1.1 National Electrical Code - 1996
      1.1.2 IEEE 929 - 1988 Recommended Practice for Utility Interface of Residential and Intermediate PV Systems
      1.1.3 IEEE 519 - 1992 Guide for Harmonic Control and Reactive Compensation of Static Power Controllers
      1.1.4 UL 1741 Standard for Power Conditioning Units for Use in Residential Photovoltaic Power Conditioning Systems.
      1.1.5 UL 943 Standard for Ground Fault Circuit - Interrupters

2.0 Environment
   2.1 Temperature Range: -30°C to 50°C (-22°F to 122°F). At temperatures above 50°C, the PCS shall automatically limit its output to maintain component temperatures within safe operating limits.
   2.2 Humidity: 0 - 100%

3.0 Power Conversion System
   3.1 System Configuration (See Omnion Drawing #1264-1). The PCS shall be self-commutated utilizing insulated gate bi-polar transistors (IGBTs) in a circuit topology suitable for meeting the specifications delineated herein.
      3.1.1 DC Input
         3.1.1.1 Minimum Operating Voltage: 300 VDC
         3.1.1.2 Nominal Operating Voltage: 330VDC
         3.1.1.3 Maximum Power Tracking Range: 300 to 600 VDC
         3.1.1.4 Maximum Open Circuit Voltage: 600 VDC
         3.1.1.5 Maximum Input Current: 380 ADC
      3.1.2 AC Output
         3.1.2.1 Nominal Operating Voltage: 208 VAC ±10%
         3.1.2.2 Number of Phases: Three
         3.1.2.3 Frequency: 60 Hz +1 to -1.5 Hz

3.1.2.4 Maximum Operating Current: 300 AAC

3.2 Operating Characteristics

3.2.1 The PCS shall include the following modes of operation:

3.2.1.1 PCS Off - User Shutdown.

3.2.1.2 PCS Ready - PCS shall begin operation when all starting conditions have been met.

3.2.1.3 PCS ON - PV power flowing from the PV array to the utility service.

3.2.1.4 PCS Standby - PCS has automatically turned off due to a fault. Control system power shall remain energized. PCS shall go to the PCS Ready mode when the fault condition has been cleared.

3.3 Protection Features

The PCS will automatically go to the standby mode if a fault occurs. If the fault clears, the PCS will automatically restart after an appropriate time delay.

3.3.1 Control Protection

3.3.1.1 Over and Under Voltage:
Under Voltage Trip = 90%, Time Delay = 30 cycles
Over Voltage Trip = 110%, Time Delay = 30 cycles

3.3.1.2 Over and Under Frequency:
Under Frequency Trip = 58.5 Hz, Time Delay = 90 cycles
Over Frequency Trip = 61 Hz, Time Delay = 15 cycles

3.3.1.3 Active Anti-islanding: The inverter control continually attempts to move the operating frequency away from 60 Hz. In the absence of utility power the frequency will drift causing the unit to shut down.

3.3.1.4 Synchronization Error: PCS will go to standby if unable to synchronize to the AC line.

3.3.1.5 Over Temperature: Temperature of the IGBT heat sink is monitored. The system will go to standby if the heat sink temperature exceeds 115° C.

3.3.2 Hardware Protection

3.3.2.1 AC Surge Protection: Three 3000-joule surge suppressors with a voltage rating of 600 VAC connected from each phase to ground are used to protect the inverter from AC transients.

3.3.2.2 DC Surge Protection: One 3000-joule surge suppressor with a voltage rating of 650 VDC connected from the array positive leg to the array negative leg is used to protect the inverter from DC transients.

3.4 Instrumentation and Control

3.4.1 LCD (Liquid Crystal Display)

A 20 character 2 line LCD, visible through the enclosure cover, displays converter status (PCS ON, PCS READY, STANDBY), diagnostic messages and performance data. When the converter is operating, the display will provide information on DC voltage levels and AC power output.

Accuracy: DC Volts = 2% of full Scale

AC Watts = 3% of full Scale

3.4.2 START/STOP Switch

A START/STOP switch is located on the outside of the PCS enclosure to allow the operator to start or turn off the PCS.

3.4.3 Maximum Power Tracking

Maximum power tracking circuitry is provided to adjust the DC operating voltage of the PV array to achieve the maximum power out of the PV array at any given moment.

3.4.4 Automatic Start-up/Sufficient Solar Power

The PCS will automatically start when there is sufficient array power to offset system tare losses.

3.4.5 Automatic Turn Off/Insufficient Solar Power

Conversely, when there is insufficient array power, the Series 3300 PCS will automatically turn itself off and go to the PCS Ready.

3.5 PCS Performance

3.5.1 The PCS tare losses when in the Ready or Standby modes shall not exceed 40 watts.

3.5.2 PCS efficiency at nominal input and output voltages:

% Nominal Output	Typical Efficiency
40	95.0
60	95.0
80	95.0
100	95.0

3.5.3 The PCS power factor measured at its output shall be greater than 0.95 (lagging or leading) when operating above 25% nominal rated output.

3.5.4 The PCS generated harmonics measured at its output when operating above 25% of nominal rated output shall not exceed a total harmonic current distortion of 5%.

3.5.5 Maximum Audible Noise: 68 dBA or less at two meters.

3.6 Construction

3.6.1 The inverter shall be supplied in a NEMA 3R outdoor enclosure.

PCS Dimensions: 72"H x 60"W x 28"D (approx.)

PCS Weight: 700 lb. (approx.)

4.0 Optional Equipment

4.1 DC Disconnect Switch

A "load break" DC disconnect switch shall be supplied to isolate the PCS from the PV array for servicing purposes. The disconnect switch shall be capable of being padlocked and shall contain visible break contacts. The disconnect switch shall be mounted on the exterior of the PCS enclosure.

4.2 AC Disconnect Switch

A "load break" AC disconnect switch shall be supplied to isolate the PCS from the utility service. The disconnect switch shall be capable of being padlocked and shall contain visible break contacts. The AC disconnect shall be mounted on the exterior of the PCS enclosure.

4. Isolation Transformer

A nominal 100-kVA, 380-volt output isolation transformer shall be supplied for connection to a 380-volt utility service. The isolation transformer shall be mounted inside the PCS enclosure.

4.3.1 AC Input

4.3.1.1 Nominal Operating Voltage: 208 VAC ±10%

4.3.1.2 Number of Phases: Three

4.3.1.3 Frequency: 60 Hz +1 to -1.5 Hz

4.3.1.4 Maximum Operating Current: 300 AAC

4.3.2 AC Output

4.3.2.1 Nominal Operating Voltage: 380 VAC ±10%

4.3.2.2 Number of Phases: Three

4.3.2.3 Frequency: 60 Hz +1 to -1.5 Hz

4.3.2.4 Maximum Operating Current: 130 AAC

4.4 RS232 Interface

An isolated RS232 interface shall be provided to permit remote monitoring of the system. All information available on the LCD shall be available on the RS232 bus. The connection to the RS232 interface shall be in the AC disconnect enclosure.

4.5 DC Ground Fault Detection

A DC ground fault detection circuit shall be supplied that will cause the PCS to alarm and go to Standby upon detection of excessive PV array ground current. The trip level is field adjustable (2 to10 ADC) via the optional RS232 interface. The DC ground fault detection circuitry will ground the negative leg of the PV array. An isolation transformer is required with this option.

4.6 AC kWhr Meter

An AC kWhr meter with ±1% accuracy shall be supplied. The AC kWhr meter shall be mounted on the exterior of the PCS enclosure.

5.0 Factory Testing

The PCS shall be tested to demonstrate satisfactory operation of its control system and its ability to be automatically synchronized and connected in parallel with a utility service. Each unit shall be subjected to a heat run of at least eight hours.

6.0 Operation and Maintenance Manual

One copy of a detailed Operation and Maintenance (O&M) Manual shall be submitted.

7.0 Packing and Transportation

Shipping Weight and Size of Boxes:

7.1 PCS Weight: 900 pounds (approx.)

7.2 PCS Dimensions: 80"H x 66"W x 32"D (approx.)

Appendix G - Series 3300 Benefits Relative to the Series 3400

Development Benefits Summary **PCS Model 3300 vs. 3400**
1) The Semikron SKiiP bridge is offered in many different capacities. At the conclusion of this development Omnion can offer different capacity products with little additional development cost. Each new offering will require re-sizing of power train components and repackaging. However the controls, reliability issues, and product manufacturing processes will remain the same. SST had anticipated coming out with different capacity bridges but when this would occur was never certain.
2) The SKiiP bridge offers better temperature protection than can be achieved using IGBT modules.
3) The SKiiP bridge requires substantially less volume for the same capacity. Denser packaging should lead to downsizing of the enclosure and some marginally cost savings.
4) The SKiiP bridge is already in high volume production and is, consequently, very competitively priced.
5) With higher volume production comes the potential of higher reliability.
6) Better thermal coupling between the IGBTs and heat-sink reduces the size of the heat-sink and/or the volume of air required for cooling.
7) Integrated current sensors may be available for control purposes thereby eliminating the need for additional sensors

Development Benefits Summary 3300 vs. 3400

Appendix H - Lessons Learned Report

DGP
6/2/98
Lessons Learned

This document presents the lessons learned in our effort to incorporate soft switching into our next generation three phase photovoltaic utility grid connected inverter. There are three sections, development philosophy, sub contractor relationship, and technology problems.

SST started our contract with several end products in mind. One product was the PV inverter, but they also were interested in active harmonic canceling devices, voltage regulators, and motor drives. This caused them to attempt to build a core module that allowed application in each of these areas. While this sounds good, Omnion has found that it is very difficult to solve multiple application areas while starting a ground up design. We consulted SST to do a point design and after this design was running, expand the capability. SST choose to attempt the multiple application core module. The result was a control board that has major sections that were never used like a DSP interface, while the sections that were used have many errors in the design. This design effort has reinforced the Omnion belief that you should only solve the problem you must solve, wait for the next problem to occur before you solve it.

Our relationship with SST has had problems due to the highly advanced nature of the work and the people involved. Professor Divan is one of the world leaders in the field of power electronics. As a professor, he is use to being the teacher, with the rest of the world as his students. This has caused him to be a poor listener, and so the experience that Omnion brings in developing power electronics was not used. Even within SST industrial experience was not utilized. This is evidenced by the design of the fault annunciation on the core module, Bob Schneider of SST pointed out that the design had a problem, but he was not listened to and the design was not corrected. This has resulted in nuisance trips that could easily been avoided.

The biggest problem was the hardware that resulted from the development. Below each problem is discussed:

- Clamp Device: Our first indication that there was a problem with the development was a problem with the clamp device. We were told that the clamps were failing at a very high rate. The best life of a clamp device was 5 minutes, the worst was several 60 Hz cycles. It took SST several months to 'overcome' this problem. We thought that the problem was solved, however when we started to operate another Resonant Link PCS (RLPCS) in a battery system, we found that the problem still existed. In this system the clamp life was one to two hours. SST claimed that the devices were getting too hot, so we reconfigured the system to run them cooler. This helped, but we needed to get them so cool that it caused us to re-evaluate the basic core module rating. We finally got the heat sink for the clamp down to 60°C.
- Temperature Rating: With a heat sink temperature maximum of 60°C application at high ambient temperatures is difficult. This is much cooler than a hard switched device that can run with a 100°C heat sink. Even at this 60°C heat sink temperature, one device failed after 24 hours of operation in the battery system. Ratings using the 60°C maximum allow a core

module rating of 100kW at a 45°C ambient, but this value de-rates to 70kW in a 50°C ambient. This is only if the air flow is done in an ideal way.

- Packaging: Core module packaging did not consider outdoor application. The only way to apply the core module to an outdoor application is to add an air conditioner to the package. This causes efficiency problems. Repackaging of the core module was possible, but cost 180% of the original development. The biggest problem for the packaging is the lack of a seal between the heat sink side of the core module and the control and remaining power side of the heat sink. This is complicated by a fan that blows air over the resonant inductor and adds hot air to the main heat sink with the clamp. This causes a further de-rating if air from the resonant inductor cannot be separated from the main heat sink.
- Control Problems: An input command requesting 0 amps results in a 90-amp output. This is due to the control method chosen by SST. In addition, distortion in the utility voltage waveform is reflected in the output current waveform. These are bad characteristics of a system that is intended to meet IEEE 519.
- Active harmonic Cancellation: This feature, which is most readily accommodated at the bridge level, was not incorporated by SST. The problem is further compounded by SST's lack of current control. Omnion expected that SST would follow the current waveform other than some error both above and below the reference due to switching delay. The control that was delivered did not follow the reference. This makes it difficult to use the difference between the output waveform and the reference as a signal that shows the harmonics. Omnion typically uses the difference between the desired waveform and the actual waveform to clean up the actual waveform. Active harmonic cancellation is necessary when capacitors are used to clean up the high frequency current that results from switching, and the capacitors resonate with the utility line. In this case this is compounded by the control that adds harmonics when the utility is distorted.
- Fault Processing: Numerous phantom faults are communicated by the SST controls. This causes the inverter to shut down when nothing is wrong. In the PV world, we are attempting to increase the reliability of a system. To get the battery system to operate, the power supply under voltage trip had to be eliminated late in February 1998.
- DC Power Supply: This feature, which Omnion argued against during the development, adds cost and complexity. Start-up sequences for typical utility interconnected applications necessitate incorporating an additional power supply further increasing cost and complexity.
- DSP Interface: While trendy, this approach adds cost and complexity with few tangible benefits for the applications Omnion addresses.
- Boost Converter: On the basis that a boost converter would be lower in cost and higher in efficiency than a second RDCL, Omnion and SST jointly decided early in the development to add a front end boost converter to achieve the 100 kilowatt system rating. Several versions of the boost converter were delivered but none ran more than thirty minutes or at more than 50 kilowatts.

Appendix I - Series 3300 Pre-production Summary Report and Manufacturing Process Diagram

Document No.: 901312

Title: Design Phase 3 – Item 3520; Manufacturability Review

Project: 3300

Meeting Date: September 29, 1998, 11:00 AM

Attendees: B Massey D Porter R Koker W Hunnicutt
D Stefanac J Vohar R Troyer

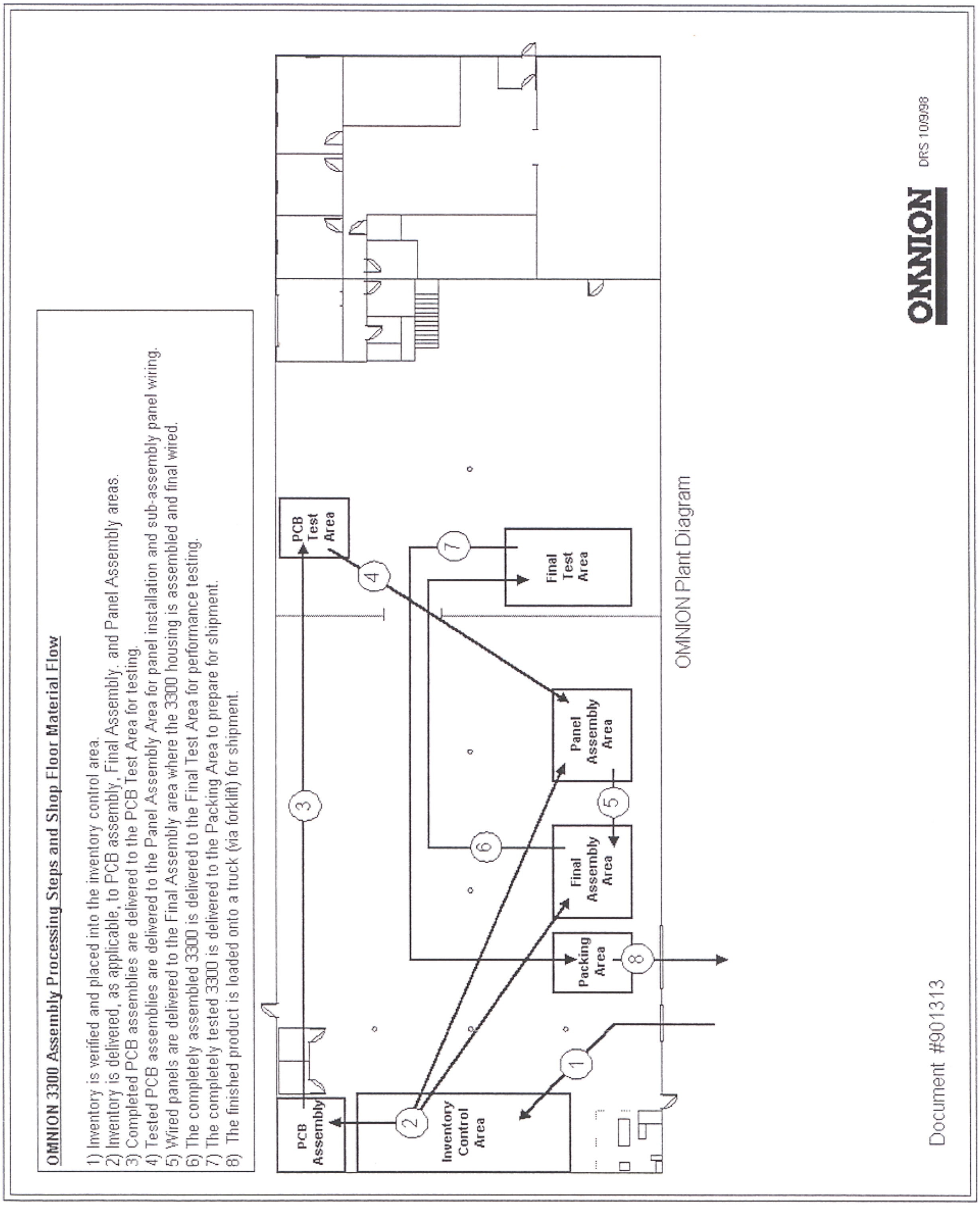
<u>Manufacturing Review Items Discussed:</u>

1) Sub-panels will be reduced from 4 to 2. (Responsible: WH, JV).
2) An air duct will be added to the inside to provide cool outside air into the upper compartment from the bottom surface. It will be located in the lower right front corner. The ground connection plate will be moved back to compensate (Responsible: WH).
3) Holes for the sub-panels will be added to the housing (Responsible: WH).
4) The AC capacitors will be moved to the shelf in the upper compartment.
5) The hole for the transformer and reactor will be moved to fill in the space left by the lower sub-panel that was eliminated (Responsible: WH).
6) The SkiipPACK bridge will be mounted closer to the center line of the chassis and the fan will be moved to the left (back) side. This allows additional components to be added to the left side of the sub-panel while maintaining a short connection path to the SkiipPACK bridge (Responsible: WH).
7) The final drawing of the fan shrouds will be created (Responsible: WH).
8) The external ground pad must be added to the drawing set (see 2 above) (Responsible: WH).
9) The LCD must be moved 1/8" to the left to eliminate the need to trim the cover label (Responsible: WH).

<u>Manufacturing Equipment Performance</u>

The 3300 was designed with consideration given to present manufacturing facilities and capabilities. The assembly of the pre-production version of the 3300 did not require and changes or additions to the manufacturing equipment. All equipment performed normally. The manufacturing process did point out several improvements (as noted above) that would eliminate portions of the fabrication effort. Similar improvements are expected as experience with higher volume manufacturing occurs.

The only change in equipment occurred prior to final testing. The PCB assembly test fixture was modified to accommodate the SkiipPACK bridge drive PCB assembly. The test was completed as expected.



Series 3300 Manufacturing Process Diagram

Appendix J - Sandia Test Report

Omnion 3300 100 kVA Grid-Tied Inverter Evaluation Report

Jerry W. Ginn

Photovoltaic System Application Department
Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185-0753

Overview

PVMat supported the development of the Omnion Power Engineering Corp. Model 3300 inverter with goals of reducing manufacturing costs in several areas. Omnion developed a 100-kW U-I power-conversion system using a highly integrated power-switching assembly with the insulated gate bi-polar transistors (IGBTs) laminated directly to the heat sink. The laminated power-switching assembly resulted in lower losses, smaller heat sinks, and reduced factory labor and assembly time. The unit's design was influenced by round-table discussions with system users, integrators, and utilities to define the most useful parameters for this product. Performance characteristics include a 93-94% peak inverter efficiency, a 300 - 600 V_{dc} input voltage window, with an operating voltage range of 252 - 308 V_{ac} at 59-61 Hz. Omnion has emphasized reliability in this product design and will use ISO9001 qualification procedures in manufacturing. The unit is designed for a calculated mean-time-before-failure design goal of 40,000 hours. The product is designed to allow optional features such as enhanced data acquisition as suggested by round-table advisors for the contract. The unit is designed to comply with applicable UL, IEEE, NEC, and FCC guidelines.. Omnion chose to incorporate an advanced SemiKron Intelligent Integrated Power (SkiiP) bridge switching package after their proposed resonant-core, soft-switching design was found to be unstable and prone to failure when coupled with the regulator circuit needed to accommodate wide input voltage windows for the different PV module technologies.

The SkiiP package offered improved hard-switched performance through integrated drive circuits, built-in device protection, and much improved thermal performance. The SkiiP allowed a significant reduction in heat sink size and inverter size. The design retains many of the soft-switched improvements in efficiency and cost, reduced time for manufacturing and test (by more than one third), and reduced parts count (by nearly a factor of two). Omnion also used a new cabinet strategy that was estimated to reduce the cost of packaging by one-fourth

Omnion's PVMaT phase 4A1 contract work ended in September 1998 but will be extended to allow for UL listing of the inverter. The inverter was delivered to Sandia for start-up tests and extensive evaluation measurements. The inverter will remain at Sandia for extensive testing and characterization before being returned to Omnion. Once returned, Omnion plans to make necessary modifications and then submit it to Underwriters Laboratories for listing.

The inverter was operated with a PV array to 25 kW_{dc} and with a battery bank to over 100 kW for the tests reported here. The inverter efficiency was measured to be 93% to 94% at input power levels above 15 kW. Current total harmonic distortion (THD) expressed as a fraction of the inverter's rating was below 4% for all power levels above 5kW. The voltage THD of the utility line at the test facility remained below 2% for all conditions tested. Conducted radio-frequency interference (RFI) was measured and found to exceed the maximum allowed by FCC with peaks at 1.8 and 5.6 MHz. Radiated RFI was negligible in the spectrum 30 MHz to 1 GHz (the FCC Part 15 frequencies of concern). The maximum power tracker circuitry accurately extracted the maximum available from the array. The anti-islanding circuitry was effective in disconnecting the inverter quickly on loss of utility under a variety of load conditions. The dc operating range was exactly as specified. The steady-state ac operating range did not correspond to the specifications as reported here. Acoustic noise was measured at 63 dB and considered extremely low for a 100-kW inverter. The cooling fans effectively maintained the heat-sink temperature below 50°C. No operational difficulties were encountered.

Issues

Electromagnetic high-frequency content

Levels of conducted radio-frequency (RF) signals on the ac conductors were as much as 40 dB above the maximum levels allowed by FCC Part 15B Class A. The FCC criteria are defined for frequencies from 450 kHz to 30 MHz. The highest peaks were at 1.8 MHz and 5.6 MHz. Radiated RF from 30 MHz to 1 GHz was negligible.

Cabinet

The removable front panels of both top and bottom sections were difficult to align. The nuts in the cabinet structure had a tendency to pop out easily.

Omnion is aware of these issues and plans to address both in future models.

Data

Data were taken in the following categories

1. efficiency
2. power factor
3. total harmonic distortion (THD) to 3 kHz
4. intermediate frequency electromagnetic noise 3 kHz to 450 kHz
5. conducted radio-frequency interference (RFI) 450 kHz to 30 MHz
6. radiated RFI 30 MHz to 1 GHz
7. maximum power tracker (MPT) functionality
8. anti-islanding functionality
9. restart time (after a power outage)
10. dc operating range
11. acoustic noise
12. temperature

Evaluation Setup

Figure 1 shows a single-line diagram of the laboratory evaluation configuration. Because only about 25 kW of PV power was available, a battery bank was used as the dc source for measurements at higher power levels. The 3300 was operated at various power levels by using a terminal emulator to command a voltage regulation of the dc bus. When a voltage level higher than the battery can maintain is selected, the inverter reduces its output power level to maintain this voltage.

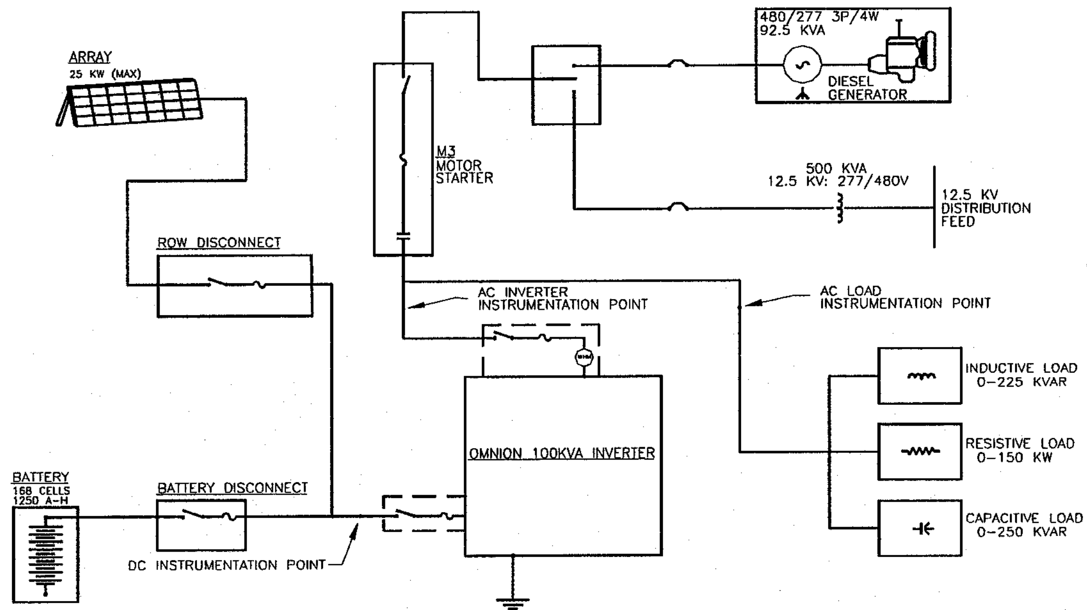


Figure 1. Simplified single-line diagram of evaluation setup

Initial turn-on

The 3300 was connected to the local utility grid and powered by an array with a peak power of roughly 17 kW. The inverter was operated unattended for ten days. No problems were experienced. Figure 2 shows the dc and ac power for one clear day.

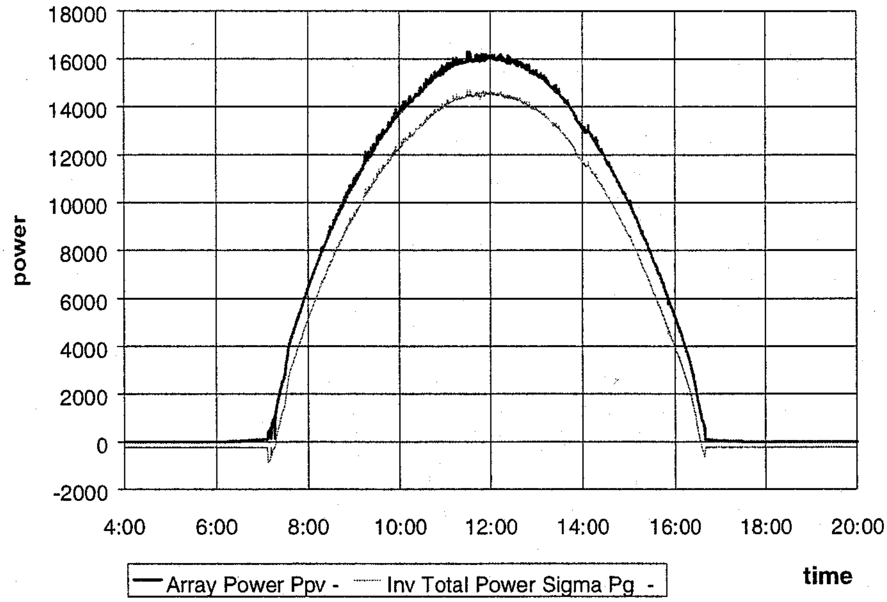


Figure 2. Dc and ac power during a clear day of unattended operation

Efficiency

Figure 3 shows efficiency as a function of ac output power. Efficiency was greater than 90% for power levels above roughly 10 kW. From 30 kW to the full rating of 100 kW, efficiency was relatively constant at 93 to 94.

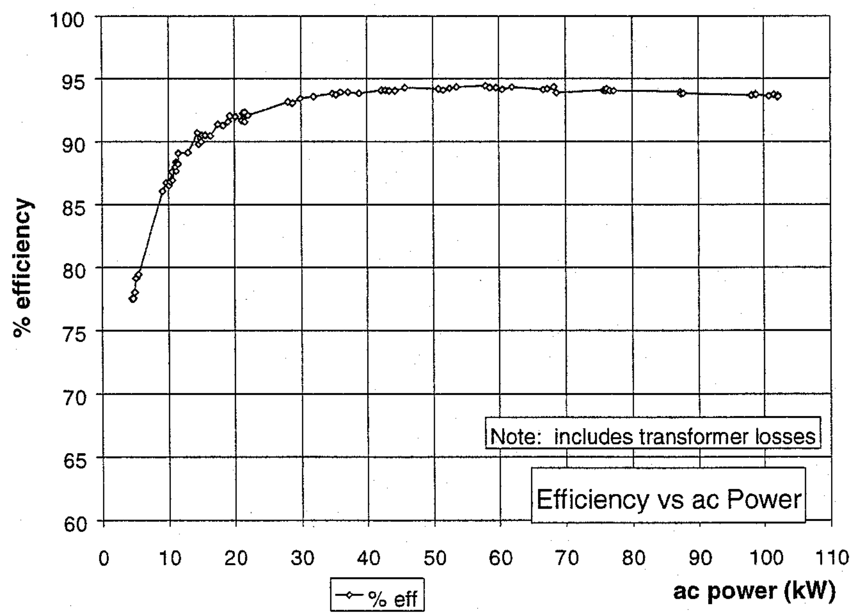


Figure 3. Efficiency vs. ac power

Power factor

Total power factor is defined as the ratio of ac power to ac volt-amperes. The power factor measurement was affected by the harmonic content of the current. Low total power factors were observed at low power levels, where the harmonic content of the output current is relatively high. For example, at 5.5 kW the power factor was 0.75. At higher power levels, as the distortion decreased, the total power factor approached unity. However, in all cases the displacement power factor (cos. θ), where θ is the electrical angle between the 60-Hz components of voltage and current, was essentially unity.

THD

Figure 4 shows the total harmonic distortion as a function of ac power for the data from Figure 1. THD is calculated using each discrete harmonic measured to the 50th harmonic (3 kHz) and expressed as a percentage of the 60-Hz fundamental. Although current THD is high at very low power levels, when expressed as a percentage of the rated current, it is well below 5% for all power levels. This is consistent with IEEE 519, which defines allowable harmonics in terms of a percentage of the maximum demand load current. Voltage THD of the test bed remained below 2% for all power levels.

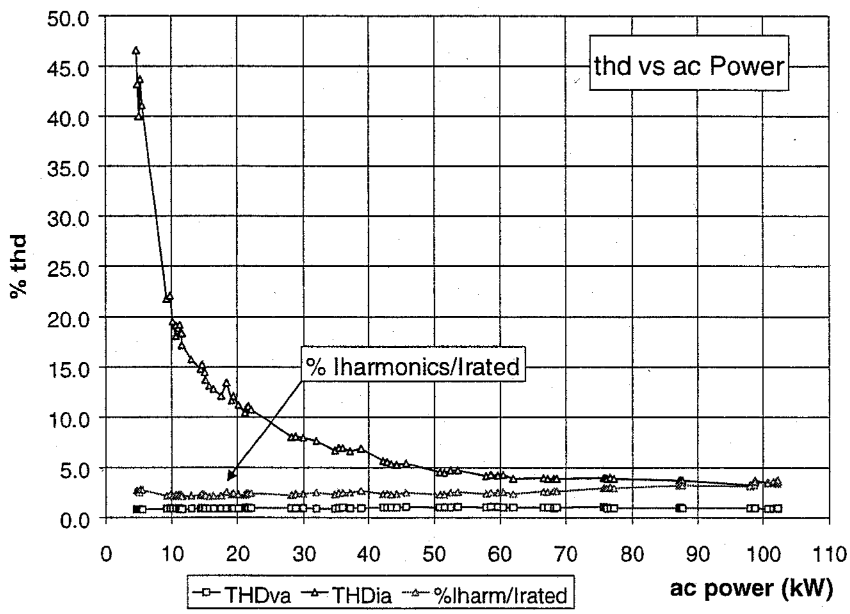


Figure 4. Distortion vs ac power

Radio-frequency interference (RFI)

Conducted (450 kHz to 30 MHz)

Measurements were taken using a Farnell SSA 1000A spectrum analyzer and a line impedance stabilization network (LISN) provided by Omnion. The LISN was placed in series with the phase A output approximately 15 feet from the ac output terminals of the inverter. Figure 5 shows the FCC Part 15B Class A maximum allowable RFI limits, background measurements, and the conducted high-frequency voltage signals present on the ac conductor when the inverter was supplying 10 kW to the grid. These results using the LISN agreed to within about 5 dB with those obtained using an EMCO model 3701 line probe.

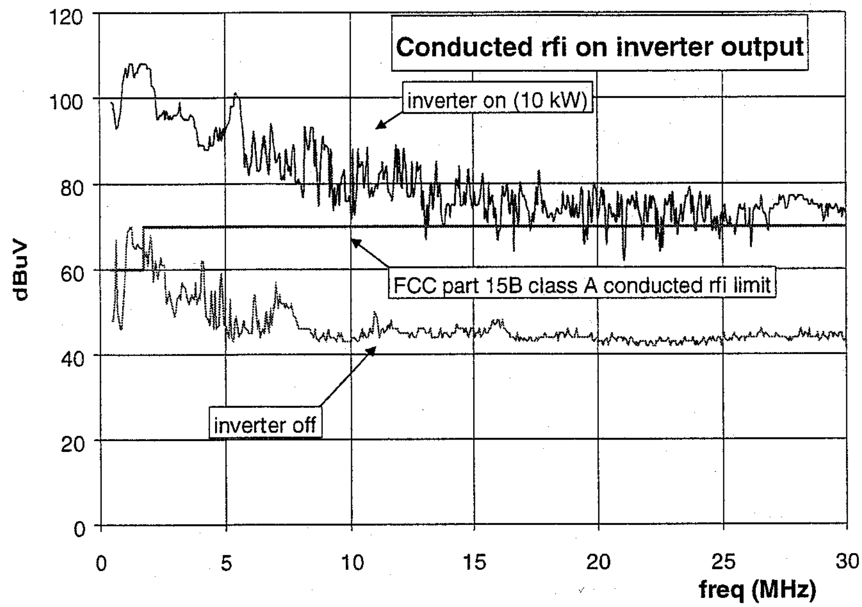


Figure 5. Conducted rfi on inverter output

The conducted voltage spectrum was also measured using a Tektronix P5200 differential voltage probe and an HP3585A spectrum analyzer. This combination was not calibrated; however, results agreed qualitatively with those from the Farnell. The two most significant peaks occurred at 1.8 MHz and 5.6 MHz. Another peak about 15 dBμV lower was located at 430 MHz. There were no significant levels below 430 MHz.

Radiated (30 MHz to 1 GHz)

Radiated RFI was measured using the Farnell SSA 1000A spectrum analyzer and Farnell model 1ESS30280 RF antenna. Measurements were taken one meter from the front of the 3300 with the front panel in place when the inverter was operating at 100 kW. Radiated RFI levels were so low they could not be differentiated from the background.

Maximum power tracker (MPT) functionality

The accuracy of the MPT was compared to the peak power measured with a calibrated I-V curve tracer. On a cloudless day, the inverter operation was periodically interrupted, a curve was taken, and the inverter was then restarted. The I-V curve tracer measurement of maximum power was compared to the average inverter dc power before and after the interruption. There was good agreement. Results are shown in Table 1.

Curve tracer Pmax	Inverter dc power	% error
7000	6790	3.0
13800	13400	2.9
20700	20300	1.9
23000	22600	1.7

Table 1. Curve tracer array power measurements vs. power drawn by inverter

Anti-islanding functionality

The time required for the unit to disconnect following a utility outage was measured for the following five cases: 1) Interruption of all three phases with a local resistive load; 2) interruption of all three phases with a local resonant RLC load; 3) interruption of a single phase with a local resonant RLC load, 4) a resistive load mismatched to the inverter output by 50%, and 5) reactive loads with power factors of 0.95 leading and lagging. For all cases, the loads were balanced among the three phases. The utility was interupted by opening the contactor M3 in Figure 1. In order to open a single phase, the contactor was bypassed for the other two phases. Results below are compared to guidelines being developed for the proposed new IEEE Std.929 designated as IEEE PAR929 throughout this report. Although IEEE PAR929 is intended to apply only to single-phase inverters under 10 kW, it is still referenced for purposes of comparison, since there is no comparable standard for large 3-phase utility-interactive inverters at this time.

Matched resistive load

With the inverter operating at various power levels, a resistive load was applied such that the power generated by the inverter, Pg, was slightly greater than the load power, Pl. Figure 6 shows waveforms for inverter voltage and current on phase A and a trigger signal that transitions from 0 to 5 V when the grid contactor was opened. Because of a delay in opening auxiliary contacts associated with the trigger signal, the grid voltage is actually removed approximately ½ cycle before the trigger transition. Disconnect times were measured from the opening of the grid contactor until the inverter current dropped below an arbitrary level of 4 A, indicating that the inverter has disconnected. Figure 7 shows disconnect times for seven measurements with Pg/Pl ratios between 1.002 to 1.052. All were well below the 2 seconds proposed by the draft for IEEE PAR929.

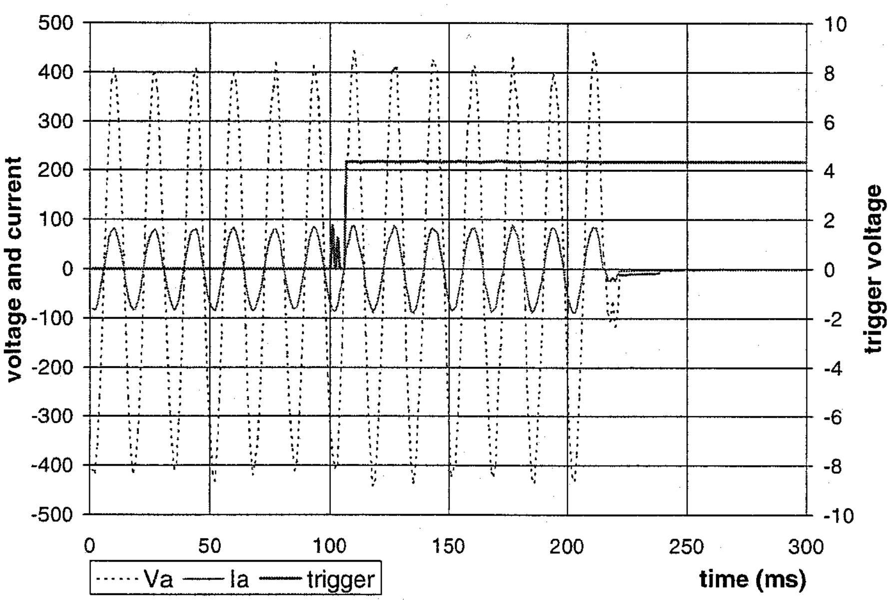


Figure 6. Disconnect waveforms for matched 49-kW resistive load

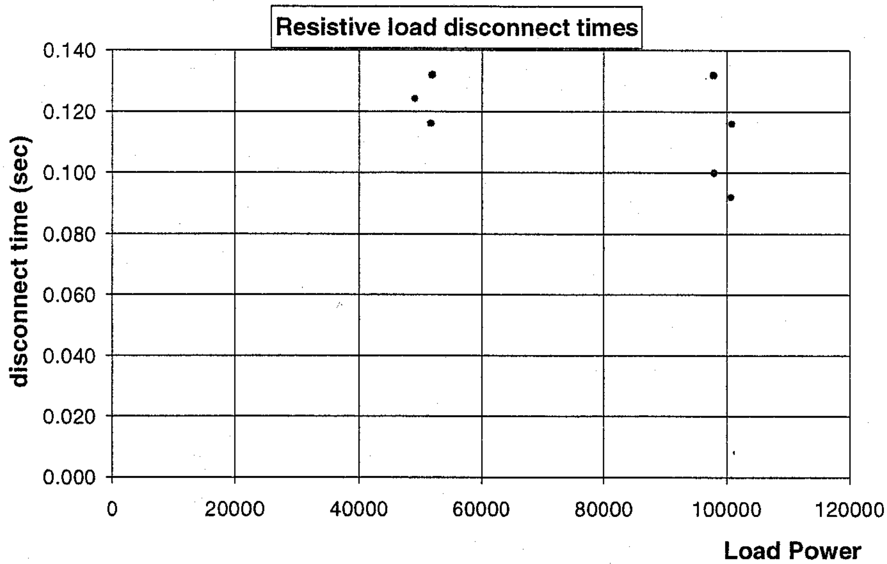


Figure 7. Disconnect times for matched resistive load
Note: The IEEE PAR929 maximum-disconnect time is 2 seconds

Resonant RLC load-disconnect all three phases

With the inverter operating at different power levels, an RLC load was applied such that the inductive reactance at 60 Hz was equal to the capacitive reactance at 60 Hz. This is intuitively a difficult case, as the loads act to create a 60-Hz voltage waveform even in the absence of the grid. A purely passive islanding-detection scheme will not detect a utility outage with this load condition. The test becomes more difficult as the load becomes less damped, since an undamped (P=0) load would oscillate indefinitely at 60 Hz. The IEEE PAR929 recommendations set the "worst-case" (maximum Q) limit for damping at Q=2.5, where Q is the ratio of VARs (either L or C) to watts.

The test procedure was as follows:

1. A capacitive load was applied.
2. Inductive load was increased until the net VARs at 60 Hz were zero.
3. A power output from the inverter was selected by commanding the dc bus regulation voltage.
4. A resistive load was applied to match the power output of the inverter.

Once the VARs are applied, the resonant quality factor (Q) depends only on the power. Therefore, different data points could be obtained with fixed values of L and C. As in the resistive-only case, resistive load was applied such that the power generated by the inverter, Pg, was kept slightly greater than the load power, Pl. Figure 8 shows the same set of waveforms as those of Figure 6 for a 60-Hz resonant RLC load with Q = 6.9. Figure 9 shows disconnect times for 41 measurements with Pg/Pl ratios between 0.99 to 1.34. As noted, for one portion of the data the reactive load was 201 kVAR, and for the remainder of the data the reactive load was 154 kVAR.

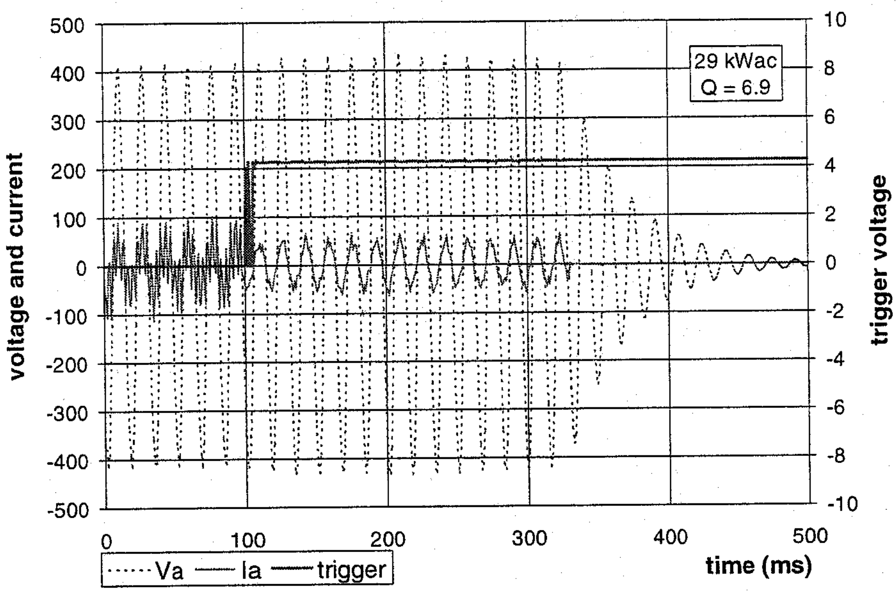


Figure 8. Disconnect waveforms for resonant RLC load with Q = 6.9

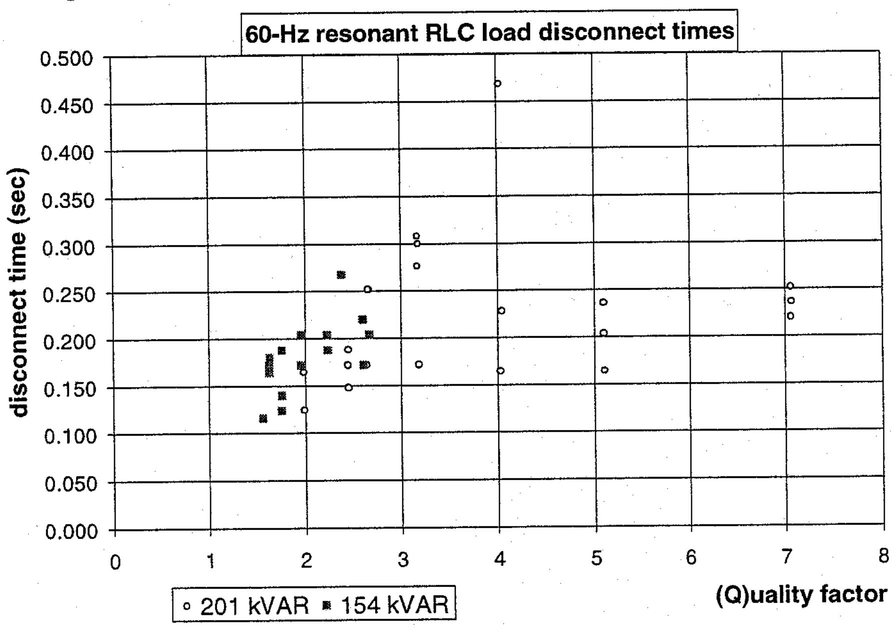


Figure 9. Disconnect times for 60-Hz resonant RLC load

Note: Proposed IEEE 929 maximum disconnect time is 2 seconds for Q < 2.5

Resonant RLC load-single-phase disconnect

The resonant RLC test was repeated but only phase B of the utility was interrupted. The controller of the 3300 measures frequency only on phase A. Figure 10 shows a case with a resonant Q of 4, for which the inverter did not disconnect. Note that this value of Q is outside the IEEE PAR929 test criteria and is extremely unlikely to occur on a utility grid.

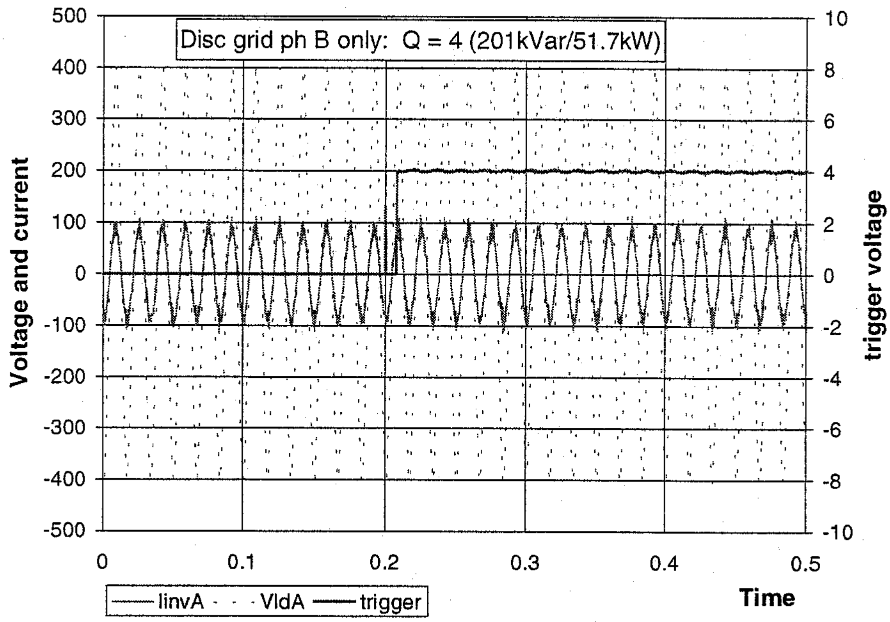


Figure 10. Single-phase utility disconnect. Inverter ran on indefinitely with resonant Q = 4.

Figure 11 shows another disconnect of phase B only, this time with the resonant Q = 2.1. This value is within the IEEE PAR929 disconnect criteria. For this case, the inverter turned off in less than two cycles.

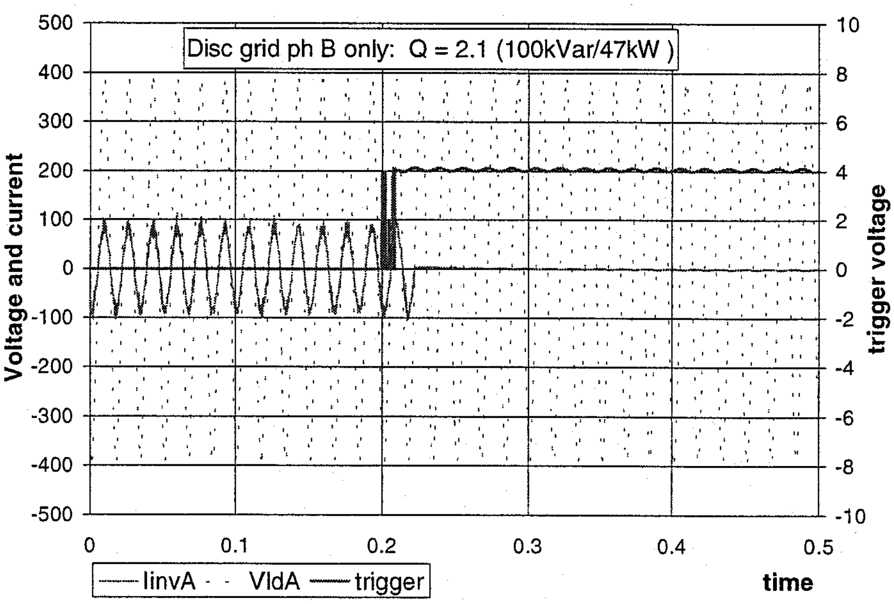


Figure 11. Single-phase utility disconnect. Inverter off quickly with resonant Q = 2.1
Note: IEEE PAR929 maximum-disconnect time is 2 seconds for Q < 2.5

Resistive load with 50% mismatch

The IEEE PAR929 criteria calls for the inverter to turn off in ten cycles when the utility is disconnected with a resistive load in place that is either less than half or more than double the inverter output. The 50%-load case was tested with the inverter operating at 100 kW and the load at 50 kW. The 200%-load case was tested with the inverter operating at 24 kW and the load at 48 kW. Data is summarized in

Figure 12. One of the 200%-load disconnect times was very close to the 10-cycle limit; the others were well below it.

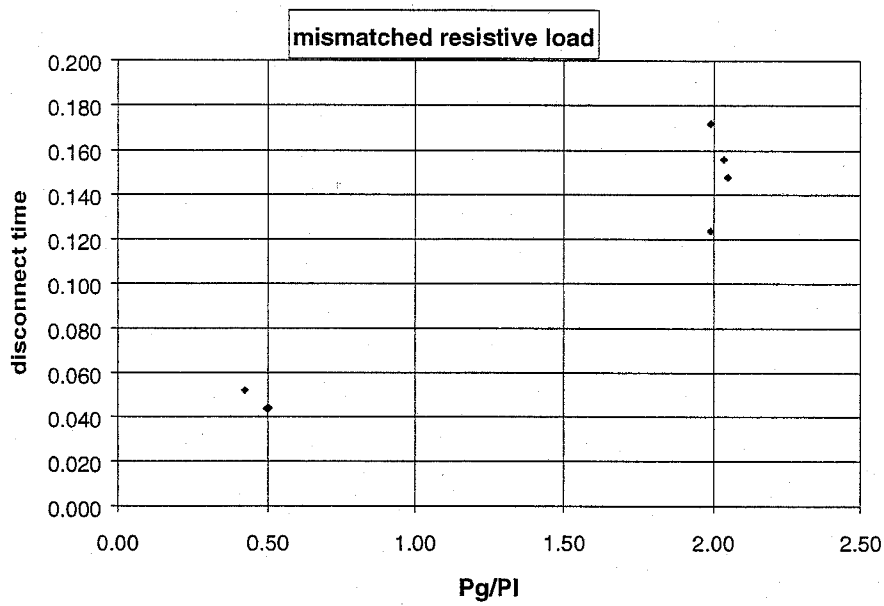


Figure 12. Disconnect times for a 50%-mismatched resistive load
Note: Proposed IEEE 929 maximum disconnect time is 0.167 seconds

RL and RC loads with 0.95 power factor

The IEEE PAR929 criteria calls for the inverter to turn off in ten cycles when the utility is disconnected with a combination resistive and reactive load in place that has a power factor of 0.95 or less. A 45-kW resistive load was used for these tests. Inductance was added for a 0.95 lagging power factor, and capacitance was added for a 0.95 leading power factor. For the six measurements that were made (3 leading and 3 lagging), disconnect times ranged from 36 ms to 52 ms.

Restart time

Following a power outage, as simulated by the previous islanding tests, and if dc voltage remained within acceptable limits, the inverter restarted in 2-1/2 minutes. This is shorter than the IEEE PAR929 criteria and may require some adjustments to the inverter controls.

Dc operating range

Omnion set the minimum start voltage to 350 V_{dc}. The dc voltage was increased incrementally using a dc power supply. The inverter turned on at 349.3 V_{dc}.

Ac operating range

A diesel generator was used to simulate a utility in order to measure ac voltage and frequency windows. A resistive load was placed on the generator so that it would not be forced to absorb power from the inverter. The generator frequency was changed in increments of approximately 0.01 Hz. Temporary inverter shutdowns were observed at frequencies ranging from 60.35 Hz to 60.5 Hz. Following a shutdown, the inverter sometimes would automatically restart. This lack of repeatability may have been due to interactions with the generator, which has a different output impedance than that of the utility grid. The underfrequency trip point was more repeatable at 59.0 Hz.

The overvoltage trip point was between 300 and 305 V_{ac} and resulted in a "utility overvoltage" display message. The undervoltage trip point was not as clear. When reducing the voltage, several trips were encountered at 268 V_{ac}. These were followed by automatic restarts and had no display fault message. The following table summarizes the steady-state voltage and frequency trip points.

Parameter	Specification	Measured
Overfrequency	61.0 Hz	60.5 Hz
Underfrequency	58.5 Hz	59.0 Hz
Overvoltage	304.7 V_{ac}[1]	300-305 V_{ac}
Undervoltage	249.3 V_{ac}[1]	268 V_{ac}

Table 2. ac voltage and frequency trip points

[1] Specification is 202 V_{ac} $\pm$10% before the transformer

Acoustic noise

Acoustic noise was measured one meter in front of the inverter cabinet using a Bruel & Kjaer Model 2230 Sound Level Meter with a Sound Level Calibrator. The meter was set for slow response with a type A filter. The background with the inverter off was 57 dB. The acoustic noise measured with the inverter operating at 100 kW was 63 dB. Subjectively, the noise from the inverter is not particularly objectionable. This is probably due in part to the fact that its switching frequency is not constant, but dithers over various frequencies in the few-kHz range.

Temperature

Heat sink temperature

The temperature of the heat sink on the middle SkiiP bridge was measured. The cooling fans came on at 50° C and the temperature thereafter cycled between 50° and 37° C.

Infrared photographs

A variety of infrared photographs were taken of the inside of the inverter cabinet and transformer cabinet after the inverter had been warmed up sufficiently for the fans to begin cycling. This information will be provided to Omnion separately from this report.

Summary

The Omnion 3300 utility-interactive inverter prototype was evaluated for operational parameters including: inverter efficiency, power factor, harmonic distortion of the output current, conducted and radiated radio-frequency interference, maximum-power-tracker functionality, anti-islanding functionality under a wide range of load conditions, dc and ac operating range, acoustic noise, temperature, and performance over a typical day. It is the opinion of the technical staff that this inverter design would be improved by achieving lower levels of conducted RFI. A more robust mechanical enclosure and fasteners are desirable. The bolted-together cabinet seems less substantial than welded cabinets especially for shipping, but may be an acceptable trade-off for reducing the costs of inverter hardware for PV applications. No electrical operational difficulties were encountered.