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Next-Generation Three-Phase Inverters

Phase One Annual Report, 1996

A. Wesley and R. Wills
Advanced Energy Systems Inc.
Wilton, New Hampshire



National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of
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Managed by Midwest Research Institute
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under Contract No. DE-AC36-83CH10093

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Technical Monitor: H. Thomas



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Title: **Next Generation Three-Phase Inverters**

Organization: Advanced Energy Systems, Inc.
 Wilton, NH

Contributors: Dr. Robert Wills, Principal Investigator; Adam Wesley; David Fish; Dr. Vladimir
 Brunstein; Len Wright

Introduction

The PVMaT-4a subcontract addresses the cost-effective manufacture of PV related products. Advanced Energy Systems Inc. (AES Inc.) has undertaken NREL contract #ZAF-4-14271-10, titled “Next Generation Three Phase Inverter,” to combine leading industry skill with advanced technologies to realize superior PV inverter-related products. To this end, in phase one of the PVMaT contract, AES Inc. made significant inroads toward establishing a low-cost manufacturing process of an intelligently controlled PV-hybrid product.

Briefly, the objectives laid out in the PVMaT contract include the delivery of a next generation prototype PV-hybrid inverter and PV-grid interactive inverter, as well as establishing a pilot production line for the products. The specifications for these units were developed from extensive market research. The inverters incorporate many advanced features including digital wave-shape and resource control techniques using DSP functions, optimized power magnetics, a design aimed at economic manufacturing and simple maintenance, optimized dispatch algorithms incorporated within automated system control, and a MODBUS industry standard remote monitoring and control communications capability.

AES has targeted improvements in several areas of the current inverter design that would improve the performance and reliability of the product while at the same time reducing manufacturing costs. These areas include the inverter control and drive components, the hybrid control system, the remote monitoring and control package, and the implementation of a modular “Power Block” design of the IGBT power switching sub-assembly. In addition, a manufacturing collaboration between AES and WPI Power Systems of Warner, NH has been developed. The efforts put forth in these areas under the PVMaT-4a contract have been successfully translated into commercial efforts; several commercial hybrid inverter systems that incorporate the product improvements have already been deployed and have proven to be both reliable and effective.

Digital Inverter Control

One objective for the PVMaT development was a revised inverter sinewave control card and robust IGBT drive card. The new inverter control electronics forms the basis of a refined solution that achieves higher inverter performance at a lower cost. Functionality and flexibility has been increased with the introduction of a digital microprocessor as the core of the inverter control electronics. This benefits future revisions of the system, shifting new development toward software and reducing the necessity to modify the hardware design. The clear enhancement here is the ability to introduce self-testing, automated diagnostics and the capability to store comprehensive set-up information within the core of the inverter itself.

Inverter Control Card

The revised ICC design contains two significant enhancements; the introduction of micro-controller technology and the refinement of existing analog control loops to sub-cycle control improving output

voltage regulation. The new implementation contains significant software and hardware components. These components integrate the following technologies: new PID analog feed back controller for output voltage regulation, introduction of PLD technology for protection and design simplification, digital reference generation and PLL implementation using a micro-controller, integration of three phase independent, inverter controllers onto a single PCB, and communications interface for automatic set-up and fault diagnosis.

Inverter IGBT Driver Card

PVMaT also supported the development of a new IGBT driver card which is highly robust, flexible in its application and simple to diagnose. This new component includes the following developed features: de-saturation over current detection, a new power supply design, low voltage lock-out for fail-safe power-up and power-down, plug-in connectors between driver and the IGBT module, slow gate turn off under peak current / de-saturation conditions, top and bottom drives completely isolated from input drive and 24 volt supply (which facilitates the use of spilt battery banks, effectively increasing apparent DC voltage of the system without raising safety concerns), individual top and bottom high current de-saturation sensing (shut-down in 20 to 30mS) or medium current over-current limiting (adjustable shut-down, default to 1.5 seconds), LED indicators for current limiting, gate drive operation and all power supplies to assist in fault analysis and fault location.

Summary

The benefits gained in the area of digital inverter control can be measured in terms of cost reduction, performance improvement, flexibility, and reliability. Over a 60% cost reduction was realized when the inverter control design moved from four circuit boards down to a single circuit board. This provides the added benefit of improved reliability by significantly reducing the number of interconnections in the system. The MTBF for commercial systems using the new inverter electronic design will be improved markedly. In terms of performance improvement, the voltage regulation associated with the new IGBT driver cards has driven the typical THD from 10% on older systems to less than 3% for systems using the new cards[1]. Flexibility and reliability were both improved with the incorporation of microcontroller-based software control in the inverter control card. This added flexibility by providing the capability to tune the control for different applications. Reliability has increased with the addition of an RS232 communications interface to the inverter core, which provides the capability for automatic set up and fault diagnosis.

Hybrid Control System

The objective for PVMaT development on the hybrid control system was to revise the control hardware and software to make the control features more reliable, flexible, and adaptable. The efforts for meeting those objectives include the following: extending the available microcontroller RAM and program ROM from 32K to 128K each, converting the bulk of the control software from assembly code to 'C' code, incorporating a standard MODBUS communications protocol software unit into the control software, enhancing the software data logging module, and developing a Hybrid Environment Simulator task that runs on the same platform as the rest of the control software. In addition, the software development environment was improved by migrating the code to a commercial compiler and debugger that is recognized as an industry leader.

Extended Memory Banking

The addition of three 32K banks of ROM to the existing one 32K bank has greatly improved the potential flexibility of the hybrid control software. Due to memory constraints, previous software incarnations were comprised mainly of assembly-language code. The difficulty in designing, modifying and maintaining assembly code is much higher than the code of a higher-level language such as C. Adding the extra memory provided the opportunity to convert the assembly code to C, and further, allowed the data logging module of the control software to store over a month's worth of data sampled at 15 minute intervals. The extra memory also served as a cost reduction vehicle, since the separate LCD and keypad interface card in earlier systems was eliminated when the software supporting those devices was moved onto the control system microcontroller.

MODBUS Communications Module

The addition of a standard MODBUS communications module to the software adds to the reliability and flexibility of the control software by providing a standard communications interface between the control software and other MODBUS applications, such as a remote monitoring and control system.

Hybrid Environment Simulator (HES)

The addition of the Hybrid Environment Simulator (HES) task to the control system software has greatly improved the reliability of the software by providing the capability to thoroughly debug and test the software without requiring a real system on which to run the code. With the HES running, AES engineers now have the ability to make changes to the software, compile it, download it via a ROM emulator to a single-board test bed, and test the changes while sitting at their desks. The interrupt-driven task can be configured to run scenarios that vary the simulated generator and battery readings so that different control and dispatch algorithms can be easily modified and tested. As a case in point, when the control code developed on PVMaT was tested on the PV-hybrid prototype for the first time after being run with the simulator there were very few coding errors that needed to be corrected.

Remote Monitoring System

The objective defined under PVMaT was to implement a user-friendly remote monitoring and control system. The capability of the hybrid control software to communicate was introduced with the addition of the MODBUS communications module to the software. A consultant, Dumont Associates of Hollis, NH, was tasked with providing the other side of the communications interface, a PC-based Windows package termed SPPLink.

The ability to remotely operate or interrogate a station provides the product distributor or support group an opportunity to investigate faults and performance glitches without physically visiting the installation. Typically, site visits incur high costs, the more remote the site the higher the cost. The interface package developed extracts detailed operating information from the station controller and greatly assists in fault diagnosis. In some cases, where skilled operators are not locally available, remote operation becomes mandatory.

This enhanced package makes extensive use of windows graphics, communications and provides a user friendly control environment. The SPP-Link remote operator package interfaces the hybrid SCADA system with an MS-Access database and will automatically load remote historic performance information into a unique site database. Site operation can now be reviewed and analyzed using automated database queries. This significantly reduces the labor required to monitor and make informed recommendations regarding remote systems performance.

Prototype Design and Manufacture

Two key objectives of the PV-MaT 4A contract were the design and development of a high quality, low cost PV-hybrid inverter for US manufacture and the establishment of a local manufacturing partnership. Many design features of the PVMaT PV-hybrid prototype unit have contributed to the attainment of the first objective. The second objective has been met with the establishment of a manufacturing collaboration between AES Inc. and WPI Power Systems, although the market has not yet developed to the point where volume production is practical.

Prototype Design Features

During the design of the prototype unit, several initiatives were identified and undertaken to produce the best product at the least cost. The reduction in the number of circuit boards in the system discussed previously was an important step in this direction. Another important step was the effort to design the inverter as a collection of modular subassemblies. Three primary subassemblies were identified: the enclosure and output stage, including the transformers, inductors, and cabinet, the Power Block, which combines the IGBT devices, drivers, capacitors, and bus work mounted upon a single heat sink assembly, and the electrical looms and control harness, which includes the wiring of connections between sensing and control points. The Power Block design is the component that has proven to be the most effective design enhancement. With the new design, the potential now exists to assemble, calibrate, and test under power the most failure prone and most critical inverter subassembly. In addition, field service of IGBT-related problems has been made simpler and safer by incorporating many individual components into a pre-calibrated and pre-tested subassembly[2]. The PVMaT power block design has been used now in several AES commercial inverters.

Prototype Manufacturing Highlights

The issue of long term alliance has been discussed with WPI with a positive outlook. Both parties have contributed greatly toward achieving a successful pilot manufacturing program. The ability to draw on WPI's experience in low-medium volume, power electronic system's manufacture has already proven to have been of significant advantage over other manufacturing options. Development of substantial manufacturing documentation was considered key to realizing a reliable and repeatable product. AES and WPI have worked together to produce a comprehensive set of manufacturing documents, including a full Bill of Materials (BOM), CAD drawings of the enclosures, the physical layout, and control system schematics, all cable definitions, including cable sizing, connection types, and wire sizes and colors, and a set of specific assembly instructions.

Prototype Manufacturing Costs

The cost objectives for the production of the PV-hybrid prototype units were successfully met. The actual cost to build the prototype came in at \$0.37/kW, which was well below the target cost of \$0.45/kW.

Commercial Benefits

An important method of measuring a research project's success is by analyzing how well the design initiatives of a project translate into the design features of commercial products. In this regard, the PVMaT contract would have to be deemed an overwhelming success. The pre-existing product line has

been totally re-defined to include many of the design improvements made possible by the PVMaT-4a project. Commercial inverters with the new design features have already been deployed and have proven to be reliable, safe and effective.

References

1. R. Wills, A. Wesley, "PVMaT Project 1996 Annual Report", pp. 16-17.
2. R. Wills, A. Wesley, "PVMaT Project 1996 Annual Report", pp. 28-29.

Advanced Polymer PV System

Highlights

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Evergreen Solar, Inc.

Goals

Under this two-year PVMat Project, Evergreen Solar's goals were to develop:

- A new backskin material that would allow the use of a frameless module;
- Innovative mounting methods utilizing the new backskin material;
- A new encapsulant to replace ethylene vinyl acetate (EVA) that would not require vacuum lamination; and
- A continuous, in-air lamination method using the new encapsulant.

The company focused on backskin issues in the first year of the project and the encapsulant in the second year. Evergreen Solar completed the project in 1997, having accomplished all of its goals.

{Photo: PIX 05936 (cropped)}

{Caption:} Frameless module installation with AC inverter mounted on back.

Technology

To develop a suitable backskin material, Evergreen Solar conducted a survey of commercially available materials and selected a polymer that was already being used in other major industries, and which could be modified for use in manufacturing PV modules. The company chose a thermoplastic material that can be formed during the lamination process

to seal and frame the module edges, thereby eliminating the need for an aluminum frame. The backskin is about 1 mm thick over the rear surface of the module and about 3 mm thick around the edges of the module. This setup was thoroughly tested to identify major obstacles and to ensure that the new backskin material and frameless module design would pass required qualification tests.

Using the new backskin material and appropriate lamination conditions, Evergreen Solar can obtain edge-sealed and "framed" modules directly from the lamination step. Commercial 30-W and 60-W modules will be made with String Ribbon solar cells, using the company's proprietary technologies for growing silicon ribbon and processing low-cost cells [1,2].

The new backskin material enables a wide spectrum of mounting possibilities. For roof mounting, an innovative system was developed that utilizes aluminum "slide bars." These bars are bonded onto the backskin, extending a little beyond the edge of the module. The complete, frameless module is then mounted by simply sliding the module over two pieces of C-channel [3]. For pole mounting, Evergreen Solar has bonded a bent aluminum plate to the backskin and tested it for bond strength with no apparent problems. The company has also successfully and easily bonded large-area flat-head aluminum bolts. In addition, the backskin has been heat-bonded to other polymers to produce a module with no junction box; instead, the leads emerge from the backskin material at the edge of the module.

Evergreen Solar's new encapsulating material shows considerable promise as a replacement for EVA. The material can be obtained in sheets about 18 mm thick. Unlike EVA, it does not require chemical cross-linking, and consequently avoids some of the issues associated with the organic peroxide additives used for cross-linking EVA. The new encapsulant

This Evergreen Solar project is part of Phase 4B of PVMat — a cost-shared partnership between the U.S. Department of Energy and the U.S. PV industry to improve the worldwide competitiveness of U.S. commercial PV manufacturing.

can be laminated in air — unlike EVA, which requires a vacuum — and in early tests bonds very well with all adjacent surfaces. A new ultraviolet (UV) stabilization package has been developed specifically for this encapsulant and early accelerated tests for UV exposure indicate that it performs better than EVA.

Utilizing the properties of the new encapsulant, a nonvacuum, continuous-lamination method has been developed. A prototype machine that can make modules larger than 60 W in size has been designed and built and the basic process parameters determined.

{Photo: TIFF image coming from Hanoka}

{Caption:} The corner of a 60-W module showing the “framing” effect where the backskin wraps around the edge of the module and bonds to the glass superstrate on the front. To develop a feel for scale, the String Ribbon cells used in this module are 5.6 cm by 15 cm.

Results

The basic goals of the project were successfully accomplished, and Evergreen plans to introduce a new product line based on frameless modules with the new backskin material and new encapsulant.

A total of six patents were filed from work carried out under this PVMaT contract. Two of these patents have already been granted by the patent office..

Evergreen Solar developed a novel backskin material for PV modules that can replace Tedlar. The material passed all in-house reliability tests, including extensive humidity freeze testing, which is one of the most stringent environmental stress tests. The IEEE 1262 humidity freeze test involves 10 cycles of -40°C to 85°C at 85% relative humidity. But even after more than 100 of these humidity freeze cycles, the backskin edge seal and backskin-aluminum bond strength suffered no degradation. The new material paves the way for a frameless module and a wide variety of innovative and lower cost mounting methods, several of which were explored and tested.

A new encapsulant material and associated UV stabilization package were developed, and initial accelerated UV exposure tests were very encouraging. In one test, bare samples of both the new encapsulant and cross-

linked TBEC EVA were exposed to over 6000 hours of UV-A at 50°C. The EVA samples looked yellow compared to the new encapsulant. In another test, similar samples laminated between glass plates were exposed to mirror-concentrated Arizona sunlight (at five to seven times normal light levels) for about five months. In this test, the EVA samples had an average yellowness index increase of 0.53 and the new encapsulant of 0.11. A continuous, nonvacuum lamination method was developed utilizing this new encapsulant.

The net result of this two-year project will be an estimated saving of \$0.50/watt in module manufacturing costs.

Company Profile

Evergreen Solar, Inc., a fully integrated manufacturer of crystalline silicon photovoltaic modules, uses innovative technology in every aspect of solar cell manufacture. The company utilizes a continuous silicon ribbon growth technology called String Ribbon. Its patented cell-making technology is unique in the industry, and it also has a patented technology in the module area. The latter was funded by a PVMaT phase IV subcontract. The company began in the fall of 1994, is located in Waltham, MA, and now has about 40 employees. The company's founders are Mark Farber, President; Rich Chleboski, V.P., C.F.O.; and Jack Hanoka, V.P., Technology.

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- [1] R. Janoch, R. Wallace, and J. I. Hanoka, “Commercialization Of Silicon Sheet Via The String Ribbon Crystal Growth Technique,” *Proceedings of this conference*.
- [2] R. L. Wallace, J. I. Hanoka, S. Narasimha, S. Kamra, and A. Rohatgi, “Thin Silicon Ribbon for High Efficiency Polycrystalline Solar Cells,” *Proceedings of this conference*.
- [3] J. I. Hanoka, P. M. Kane, R. G. Chleboski, and M. A. Farber, “Advanced Polymer PV System,” *Proceedings NREL/SNL PV Program Review*, ed. By C. E. Witt, M. Al-Jassim, and J. M. Gee, AIP Press, N. Y. 1997, p. 859..

Cook, Gary

From: Zweibel, Ken
Sent: Monday, August 17, 1998 3:42 PM
To: Cook, Gary
Subject: FW: emissions reduction study

Is there any chance you can find this guy and ask him about his CO2 number? And maybe the others? Or ask a librarian to help...

Ken Zweibel
Thin Film Partnership
NREL
303-384-6441 (fax 6430)
Ken_Zweibel@nrel.gov

-----Original Message-----

From: Mark Petruzzi [SMTP:mpetruzzi@gmseal.org]
Sent: Monday, August 17, 1998 11:15 AM
To: Ken Zweibel
Subject: emissions reduction study

Thanks for your comments thus far!

It was a bit of a relief to hear that I was fairly on target after just a few months of research, not nearly 20 years :)

The emissions study was cited in a paper that I got from ASE Americas, Inc entitled "Photovoltaics and the Revolution in Electric Power."

However, they referenced the table from an EPA report entitled "Demonstrating Pollution Reduction Capabilities of PV Systems" by Ronald J. Spiegel in the US EPA's Air Pollution Prevention and Control Division.

Hopefully, Mr. Spiegel would be able to give you the specifics that they used.

Hope this helps.

Talk to you soon,

Mark

*IGBT - insulated Gate Bipolar Transistor
- power transistors
for inverter applications*

PLL - phase locked loop (frequency synthesizer)

PLD - programmable logic device

EPLD - erasable " " "

soft switching - a switching network that switches between AC and DC without the loss of current or voltage

PV-MaT Project 1996

Annual Report

Phase One PV-MaT Objectives

Introduction

The PV-MaT 4A subcontract addresses the cost effective manufacture of PV related end-products. Advanced Energy Systems Inc. (AES Inc.) has undertaken NREL contract #ZAF-4-14271-10, "Next Generation Three Phase Inverter", to combine leading industry skill with state-of-the-art technologies to realize cutting-edge PV inverter related products. To this end, in phase one of the PV-MaT contract, AES Inc. have made significant inroads toward establishing low cost manufacture of an intelligently controller PV-hybrid product.

Briefly, the PV-MaT program outlines this contract as delivering a next generation prototype PV-hybrid inverter and PV-grid interactive inverter, the respective specifications developed from extensive market research and integration of advanced features including:

- Digital wave-shape and resource control techniques using DSP functions
- Optimized power magnetics, smart-power components, soft-switching methods
- Designed for economic manufacture and simple maintenance
- Optimizing dispatch algorithms incorporated within automated system control
- Remote monitoring, control and service communications capability

Two broad areas of development have been investigated. First, inverter power electronic hardware and, second, the PV-Hybrid control system combining both hardware and software components. The key cost reduction objectives have included :

- Reduce cost in the manufacturing process
- Improve life-cycle costs through reduced product maintenance and performance improvements, to increase market competitiveness extending product life span
- Reduce the cost of software maintenance and future software enhancements
- Reduce cost of delivered energy from the PV-hybrid and PV-grid system

To this end, phase one of the contract has realized a prototype, low cost PV-Hybrid solution which investigated the aforementioned points and incorporates all those features deemed critical in addressing the needs of the market at large.

Phase One Executive Summary

1.0 Introduction

The overall objective of the PV-MaT subcontract is the development of next generation inverters for both the PV grid-interactive applications and PV-hybrid applications. The summary statement is simply :

To define and develop the capability to manufacture and market competitive inverter systems for PV applications.

The applicable systems for which the new inverter technologies were to be integrated was phase one, the RAHPS-type PV-Hybrid, next development of a PV grid-interactive system in phase two. The key criteria guiding phase one development are identified in the below objectives and targets. The achievements of phase one are shown adjacent to the target :

Objective	Target	Phase I Achieved
Lower Inverter Cost	\$0.30 / Watt	\$0.25 / Watt(NOTE 1)
Reduced PV - Hybrid Manufacturing Costs	\$0.45 / Watt	\$0.37 / Watt(NOTE 2)
Improved Inverter Module Value	VTHD < 5%	VTHD < 4% (NOTE 3)
Reduce Energy Delivery Costs	Reduce \$ / kWh by 15%	Revised algorithms (NOTE 3)
Reduce Installation and Service Costs	Reduced parts and inter connections	Elimination of 5 cards from existing design
Product Distinction from competition	Integration of third party support	Integrated data logging and remote SCADA
Reduced Cost of Software Control System	All 'C' based software	Development of common software modules

NOTE 1,2 Derive from Parts & Labor Invoices, NOTE 3 Using Optimum Magnetic implementation.

NOTE 4 Not yet quantified, field evaluation is mandatory in this case.

Table 1.0 Phase One Objectives and Achievements

As this document will demonstrate, phase one of the PV-MaT subcontract has contributed significantly to the commercial realization of a reliable, field-serviceable, simply constructed, low-cost solid-state inverter system. The potential for these units to become mainstream in mission critical applications is increasingly likely. Further, the focus upon the integration of PV has opened new market opportunities where sub-optimal solutions may have previously existed.

1.1 Program Outline

At the onset of the project the contract was divided into five programs. These programs were derived from the tasks outlined in the original statement of work and redefined as related activities to be distributed amongst AES Inc. group resources. The revised programs include :

Program	Activity	Original Work Statement Task
1	Product Definition	Task 1
2	Digital Inverter Control	Task 1
3	Hybrid Control System	Task 2
4	Remote Monitoring with System Control And Data Acquisition (SCADA) link	Task 2
5	Prototype Manufacture	Task 3 and Task 4

1.2 Performance Summary

The following table outlines the five major program achievements and the progress attained at the conclusion of phase one.

Program	Objective	Complete (%)	Program Achievement
1	Product Definition	100%	Next Generation Inverter specification
2	Digital Inverter	100%	Integrated three phase digital controller
3	Hybrid Control System	75%	Enhanced station control software (NOTE 1)
4	Remote SCADA	100%	Remote PC Link via Mod-bus protocol
5	Prototype Manufacture	100%	WPI completed successful manufacture of 60KVA magnetics and unit assembly

NOTE 1 Software development for initial PV-Hybrid application based on an enhanced commercial revision supplied from Advanced Energy Systems Australia, this providing fully functional operation however not yet fully featured.

Table 1.1 Phase One Program Objectives and Major Achievements

A more detailed outline of the specific accomplishments appears below. These are achievements which attributed to the successful realization of the five major programs.

These accomplishments include the development of hardware, software, product documentation and capabilities.

1. Specification of PV-hybrid product and third party components within a document defining models, performance, electrical and physical system parameters
2. Enhanced control system, LCD interface providing intuitive, multi-lingual operator support
3. Integrated high precision data and event logging capability
4. Development of Windows based SCADA software for remote monitoring
5. Significant integration and simplification of the inverter control card electronics
6. Enhanced performance of sinewave generation module that exceeds market requirements for PV-hybrid "village application" voltage regulation parameters
7. Implementation of digital control core facilitating further development of integrated self-test and diagnostic procedures
8. Compilation of comprehensive Bill Of Materials (BOM) with data-sheets for PV-Hybrid product
9. Development of specifications and production ability for magnetic components
10. Collaboration with WPI Power as a semi-custom manufacturing group
11. Development of a single-phase test inverter leg for high-power performance and design evaluation

1.3 Milestones of phase one

The task milestones listed below were defined by the original statement of work, successful achievement of which has led to the accomplishments identified above.

- m-1.1.1 Market Research to establish parameters for (Hybrid&UI) specifications.
- m-1.2.1 Review of hardware options such as digital control, soft-switching techniques.
- m-1.2.2 Complete definition of the PV-hybrid and preliminary product specifications.
- m-1.3.1 Complete new hardware developed to specifications of m-1.1.1./m-1.2.2
- m-1.3.2 Complete preliminary communications algorithms and control protocol.
- m-1.3.3 Complete Task#1. Product definition, completed specifications.
- m-1.3.3.1 Complete design for the PV-hybrid inverter.
- m-1.3.4 Complete Task#3. Product manufacturing specification including CAD drawings.
- m-1.4.1 Complete Assembly of the prototype.
- m-1.4.2 Complete communications algorithms and control protocol.

m-1.4.3 Complete Task#2. Control and communications specifications.

m-1.4.4 Complete Task#4. Prototype construction.

All phase one milestones were successfully completed.

1.4 Deliverables of phase one

Deliverables were a requirement by the contract monitor NREL. The following deliverables marked the completion of milestone and significant task activities.

D-1.1 DRAFT specification for the UI system and PV-hybrid system.

D-1.2 Deliver report detailing prototype design.

D-1.3 Deliver system specifications for PV-hybrid design.

D-1.4 Deliver Inverter construction report.

D-1.5 Deliver description of control algorithms and specifications of control protocols.

1.5 Completed deliverables of phase one

The completion dates of program deliverables and status of deliverables are shown below.

D-1.1 - Accepted as a completed deliverable. (13 May 1996).

D-1.2 - Delivered drawings as of 15th December 1996.

D-1.3 - Accepted as a completed deliverable. (1 July 1996).

D-1.4 - Completed and delivered February 1997.

D-1.5 - Completed and delivered March 1997.

1.6 Phase I Discussion

On nearing completion of phase one, it became apparent that the development of both the PV-hybrid and grid-interactive products were based on an extensive set of common prerequisite activities, technologies and manufacturing principles. As a result, phase one provides strong technical grounding for phase two developments.

The software developed to satisfy the phase one delivery schedule as described in the PV-Hybrid specification was fully functional however not fully featured. The release is based upon a commercial PV-Hybrid implementation distributed by Advanced Energy Systems Australia., a key partner in the PV-MaT project team. To achieve integration of the commercial control program with the new inverter hardware numerous software modules were developed.

The new modules were realized using a generic-product orientated software development approach. As a result module development from phase one has successfully provided a

foundation for the delivery of both fully featured software projects the hybrid and grid-interactive inverter systems during phase two.

The key achievements of phase one applicable to both the PV-hybrid system and PV grid-interactive systems, include :

- Development of generic support technologies with core controls applicable to both end-products
- Building of a relationship with WPI manufacturing group and production documentation
- Development of the manufacturer's understanding of "the products" and opening an opportunity for their "buy-in", to the final development of a superior product
- Achievement of production and validation capability of the PV-Hybrid prototype next generation inverter technologies

Both the PV-hybrid and grid-interactive products have an undeniable synergy in their core technologies. Development has progressed in such a manner as to leverage the maximum benefit from any single task. As a result of this critical approach, control system software development has "spilled" over into phase II of the program. Analysis of the synergies between the software requirements for the PV-hybrid and grid-interactive control systems indicate that over 85% of the modules will be common, the remaining 15% of code identifies the algorithms unique to each product.

The program initially identified a development, manufacture, test and deliver approach to both products. This back-to-back development approach given the identified synergisms in the power system software is clearly not optimal. It has been possible in phase one to successfully complete the next generation inverter design and prototype manufacture. However, product completion relies upon control system software completion. Therefore, phase one has achieved a complete hardware implementation, a fully functional product, however not yet fully featured. Further software development pertinent to both the PV-hybrid and grid-interactive products is required during phase two to move the existing straw-man software solution toward supporting the fully featured product. Software upgraded is achieved simply by EPROM replacement. This approach presents no significant cost penalties and facilitates initial delivery of a fully functional PV-Hybrid prototype with staggered delivery of software features.

The project schedule for phase two now reflects a shift in focus toward completing development of the generic software modules required to support both types of power conditioning system. The subsequent manufacture of the phase two PV-Grid unit will leverage phase one production efforts.

Program 1 : Product Definition (Task 1)

2.0 Introduction

This program incorporated PV-hybrid market research of North and South America and regions of Europe. The objective of the market research was to identify the shortcomings of existing PV-hybrid solutions and identify new features or technologies that would satisfy customer and market needs.

The second objective was development of a technical specification identifying the performance characteristics of the next generation inverter, PV-hybrid system, and control system for remote area application.

2.1 Accomplishments

This program centered heavily around task one and included milestones ; m-1.1.1, m-1.2.1, m-1.2.2, m-1.3.3. The results from the market research and review of technology from the contract collaborators culminated in deliverable D-1.1. and D-1.3. AES-PV-MaT Document "AES Hybrid Specification - #ZAF-4-14271-10 - Next Generation Three-Phase Inverters".

This final document detailed the functional specification of the PV-Hybrid system, and focused on the definition of the next generation inverter and control system to be developed. Detailed for completeness were third party products mandatory for PV-Hybrid and grid-interactive station operation including batteries, gensets and PV modules.

2.2 Milestone m-1.1.1 Review

To achieve milestone m-1.1.1 and associated milestones, existing solutions to hybrid installations were analyzed and four categories of market research identified.

- 1. System level requirements**
 - Various application configurations
 - Required modes and automated adjustment of operation
 - Deployment and maintenance issues
- 2. Inverter module requirements**
 - Regional configuration of output voltage and frequencies,
 - Impacts on choice of technologies
 - Requirements for parallel operation with grid and / or genset
- 3. Operator requirements**
 - Feed-back of operating information
 - Interface of unit to human operator

- International issues
- 4. End-User requirements**
- Outage tolerance
- Social impacts of electricity
- Tariff and metering options

To develop a truly effective product satisfying all stake-holders we believed that the above areas were critical for investigation. To complete the market research the following activities were undertaken throughout phase one :

- **Survey of hybrid system integrators**, those involved in the deployment, management and specification of such systems
 1. Identification of regional similarities between installations
 2. Distribution and generation similarities
- **Review of O & M life-cycles**
 1. Identification of common failures
 2. Service difficulties
- **Review of hybrid applications**
 1. PV-village power, communications sites, stand-by power, wind-diesel
 2. To identify most successful system installations, operating characteristics and modes of operation
- **Technology review**
 1. Definition of inverter performance criteria to satisfy key applications
 2. Least-cost approach without compromising quality (robustness and reliability)

2.3 Milestone m-1.1.1 Discussion

Some key findings derived from the investigations which impacted on the development program included :

- Notion of turn-key solutions, our development focused on a product that has the potential to be the center-point component within a turn-key system.
- The product is typically viewed by the customer as composed of both a capital investment and service investment, the final package must address this expectation.

- Small PV-Village systems have enormous potential throughout the world.
- Inverter systems must have controllable output characteristics to interface with end-of-line grids and gensets equipment which will exhibit erratic performance.
- Operation of these systems is undertaken by individuals with varied educational backgrounds, a step forward would be multi-lingual instruction regarding operation and fault diagnosis.
- The remote nature of installations demand the remote interrogation of facilities.
- Metering of an entire system and self-performance monitoring is preferable as per-user metering is often unwieldy.

2.4 Milestone m-1.2.1 Review

Milestone m-1.2.1 was in essence a technology review. Within a hybrid installation the inverter can be considered as the critical component providing the means to control power distribution of all energy generating sources. With this premise, technology research was undertaken into inverter designs that maximized **reliable, efficient, and flexible** operation. Improved digital technology was a key starting point for application within the next generation inverter. Digital control addresses all criteria mentioned above. The rationalization of system operation and component selection was also challenged. The ratings of components and practical realities of their operation were carefully reviewed. Key review points for this milestone are listed below.

- **Digital control review**
 1. Digital control (DSP, FPGA) or critical digital control (Analog and Digital)
 2. Cost of development, new mission critical software
 3. Issues of technology change from analog to digital
 4. Impact on automation of test and servicing
- **Performance issues, Soft-switching review**
 1. Benefits to EMI
 2. Costs to system complexity
 3. Scope of applications
 4. Existing solutions, controlled EMI, filtering and suppression
- **Reliability**
 1. Performance stability
 - Digital Noise immunity
 - Immunity to aging and component drift
 2. Inbuilt safety
 3. Issues of failure analysis

2.5 Milestone m-1.2.1 Discussion

Technology review focused primarily upon the inverter power system and the control electronics. A review of system-level control issues was also undertaken, both the NREL Hybrid 2 design package and numerous papers on optimal dispatch were investigated. Major findings are summarised below :

- Flexibility of the inverter topology by use of output transformer, allowing variable selection of output voltages, three-phase operation, single or split phase operation.
- Integration of a digital reference generator, critical to reliable and stable performance, further introducing flexibility and intelligence in the control of the inverter output waveform.
- Reliability by design, the digital core should monitor the performance of associated analog control circuits and support automated test and configuration.
- DSP and FPGA were eliminated as development time was constrained.
- Soft-switching issues were considered expensive, not yet commercially viable.
- Operating modes to be provided with varying levels of automation, from total manual operation to fully automatic.

2.6 Milestone m-1.2.2 / m-1.3.3 Review

Milestone m-1.2.2 and m-1.3.3 corresponds to deliverable D-1.1 and D-1.3. The document incorporated the new specification for both the inverter and PV-hybrid system. This included documentation on system configurations, inverter performance criteria, block diagrams, theory of operation, key drivers for the technology and requirements for third party components. The following sections were included in the deliverable based upon the work from previous milestones.

List D-1.3. Areas of investigation for next generation inverter system

1. Hybrid system topology
2. Hybrid system configurations
3. Hybrid system features
4. PV Hybrid village system
5. Proposed product options and Service agreements
6. Hybrid Station controller

Communications links between station control components

7. Operator interface
8. Integrated system performance monitoring
9. Remote system performance monitoring
10. Specification of the inverter component
Electrical, Overload, Protection, Environmental, Mechanical
11. Specification of remaining system components
Battery, PV, Genset

2.7 Milestone m-1.3.3 Review

Milestone m-1.3.3 was used to mark the completion of Task #1 - Product definition. This milestone was achieved by defining the components of the proposed product "package".

2.8 Task One Discussion

The results of market research and the development of the PV-hybrid specification formed a basis upon which to refine the activities in the tasks remaining as outlined by the broad statement of work.

The objectives for development within the digital inverter, hybrid control system and SCADA remote communication programs originated from the successful completion of the deliverable.

Further, the completion of the specification has had benefit to the AES marketing and sales group. The document has had direct benefit in the preparation of tender specifications, RFPs and provides detailed technical information for our manufacturing partner and in the future, system integrators.

Program 2 : Digital Inverter Control (Task 1)

3.0 Introduction

This program addresses the integration and enhancement of the inverter electronic control and drive components. The objective for development was a revised inverter sinewave control card and robust IGBT drive card.

The new inverter control electronics form the basis of a refined solution using evolved designs to achieve higher inverter performance at a lower cost. Functionality and flexibility has been increased with the introduction of a digital microprocessor as the core of the inverter control electronics. This benefits future revisions of the system, biasing new development toward software and reducing the necessity to modify the hardware design. The clear enhancement here is the ability to introduce self-testing, automated diagnostics and the capability to store comprehensive set-up information within the core of the inverter itself.

3.1 Milestone m-1.3.1 Review

The performance criteria for the electronic control and IGBT drive modules were established with the previous milestone. New component design was collaborated between Australia and within the US partners. The design has undergone two revisions. The prototype version used an 8Mhz micro-controller. This proved to limit the capabilities of the software to single phase control only. This provided a significant technical challenge which was overcome by utilizing hardware internal to the micro-controller, and moving to a higher performance version of the same device. The inclusion of a PLD to support the use of internal controller hardware became mandatory in the second revision and provides some secondary benefits described below. The final revision incorporated both these changes and modifications to the drive stage to support two versions of drive card. This new module has been successfully tested.

3.1.1 Inverter Sinewave Control Card

The Inverter Control Card (ICC) has evolved from initial commercial designs developed at AES Ltd. in Australia. The revised design contains two significant enhancements, first, the introduction of micro-controller technology, second, the refinement of existing analog control loops improving output voltage regulation. The new implementation contains significant software and hardware components. These components integrate the following technologies :

- New PID analog feed back controller for output voltage regulation
- Introduction of PLD technology for protection and design simplification
- Digital reference generation and PLL implementation using a micro-controller
- Integration of three, phase independent, inverter controllers onto a single PCB
- Communications interface for automatic set-up and fault diagnosis

3.1.2 Inverter IGBT Driver card

This new component includes the following developed features.

- De-saturation over current detection (fully implemented)
- New power supply design
- Low voltage lock-out for fail-safe power-up and power-down
- Plug-in connectors between driver and the IGBT module
- Slow gate turn off under peak current / de-saturation conditions
- Top and bottom drives completely isolated from input drive and 24 volt supply.
Facilitating the use of spilt battery banks, effectively increasing apparent DC voltage of the system without raising safety concerns
- Individual top and bottom high current de-saturation sensing (shut-down in 20 to 30mS) or medium current over-current limiting (adjustable shut-down, default to 1.5 seconds)
- LED indicators for current limiting, gate drive operation and all power supplies to assist in fault analysis and fault location

PV-MaT supported the collaboration of AES Inc., Vladimir Brunstien, of Advanced Power Associates formerly with EG&G and Len Wright of L & M Electronics sole contractor for AES Ltd. Australia to develop a new IGBT driver card which was highly robust, flexible in its application and simple to fault diagnose.

The initial design attempted to incorporate fibre-optic drive communications, however this was not found to be cost effective given the constraints of the prototype. Key issues that led to this conclusion include :

- Isolation considerations : a key issue typically solved using fibre-optic isolated drive. An alternate solution currently in use by AES Ltd. uses opto-coupling and is commercially proven to provide reliable isolation for systems with power ratings consistent with the prototype.
- PCB connector space, the FRC (flat ribbon cable) approach makes effective use of board space and has little placement constraints when compared to fibre-optic connectors which occupy significant board space.

3.2 Discussion

The results of the final design implementations have been verified using existing Australian AES Ltd. inverter systems. The performance results have confirmed those defined in the initial specification. A performance review is included in Tables 3.1 and 3.2.

The design and development of the revised inverter electronics focused on three key criteria ; **reliability, cost reduction and application flexibility**. Reliability issues were addressed with lessons learned via commercial experience with inverter electronics and in the identification of common failures. Cost reductions were achieved in three manners, reduction in component count, assembly time, and time taken in the set-up and verification procedures. Flexibility of the development translates into how simply a new core technology can be leveraged to satisfy other applications.

3 phase SPP (revision 2.0)

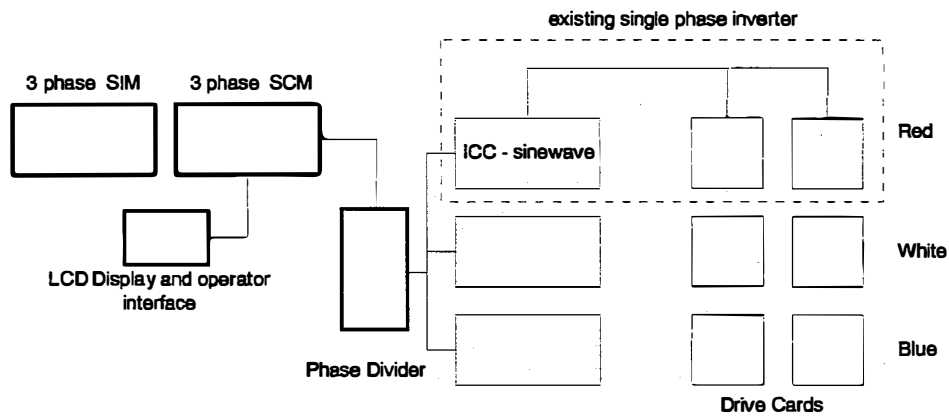
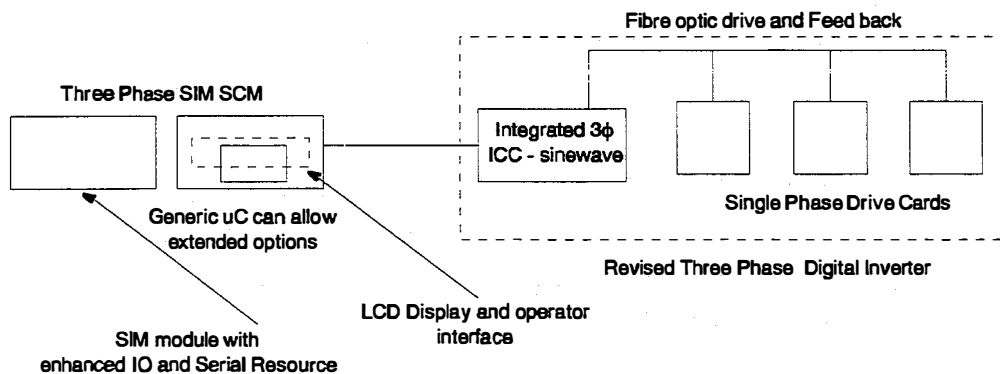


Figure 3.1 Existing three phase Hybrid Inverter Topology and PCB allocation.

PV-Mat Revised 3 phase Hybrid (revision 3.0)



A significant cost reduction was achieved by developing a digital inverter core which integrated the function of three single phase control electronics into a single card. The reduction in component requirements, the removal of duplicated power supply units, and dramatic decrease in interconnections provided a 60% cost reduction over the existing implementation. The physical layout of the pre-existing electronics solution and revised solution are shown for comparison in figures 3.1 and 3.2.

The integration of the inverter control module from four controllers to one significantly reduced the number of interconnections in the system. Connectors are a key reliability concern. Reducing the total connector count has improved total MTBF reliability markedly.

Provision of a digital RS-232 interface into the inverter core provides a means of automating set-up and introducing self-test procedures from a PC. This feature also facilitates remote diagnostics, dramatically reducing the need for skilled service personnel.

Extensive use of LED fault indicators was made to assist field servicing with rapid failure analysis. Sub-circuits key to system operation identify normal operation with illuminated LED indicators. Indicators not lite assist in isolating faults to specific cards and components.

In summary, this program has made significant improvement to the reliability of inverter control electronics and has also realized a 60% cost reduction for the revised electronics over the existing solution. Further, a significant improvement in voltage regulation as indicated by Total Harmonic Distortion (THD) from values as high as 10% to values consistently less than 5%. (see table 3.1, 3.2)

3.3 Digital Inverter performance review

OUTPUT LOAD	OUTPUT VOLTS	OUTPUT kW	OUTPUT kVA	OUTPUT PF	OUTPUT THD	DC VOLTS	DC AMPS	DC WATTS	PRIMARY AMPS	EFFICIE NCY
No load	244	-	-	-	1.2%	129	0.54	0.070	8.0	-
2kW resistive	242	2.01	2.01	1.0	1.6%	126	17	2.142	29.2	93.84
4kW resistive	242	4.13	4.13	1.0	1.6%	122	35.7	4.355	58.0	94.82
6kW resistive	241	6.11	6.11	1.0	1.6%	121	54.3	6.570	84.0	92.99
8kW resistive	240	8.34	8.34	1.0	1.8%	119	76.4	9.092	116.0	91.73
Air conditioner	245	0.86	0.94	0.91	1.0%	124	7.8	0.967	13.8	88.92
Air conditioner plus 2 motors	239	1.14	1.57	0.73	1.5%	124	10	1.240	19.3	91.94
Air conditioner plus 2 motors plus 2kW	239	3.10	3.30	0.95	0.9%	122	27.3	3.331	45.0	93.08
Fluorescent bank	242	0.25	0.51	0.50	0.8%	123	2.4	0.295	5.1	84.69
Fluorescent bank and 2kW resistive	241	2.16	2.20	0.98	0.8%	123	19.1	2.349	31.5	91.94
Fluor bank, a/c plus 2 motors	237	1.38	2.02	0.68	1.7%	123	12.3	1.513	25.0	91.22
Capacitor bank (120uF)	252	0.03	2.71	0.01	3.9%	125	2.3	0.288	45.0	10.43
Heat gun on 50% power (half wave current)	243	0.77	0.84	0.92	1.7%	124	7.1	0.880	15.5	87.46

Table 3.1 Next generation inverter control electronics performance test.

3.4 Analog Inverter control electronics review

OUTPUT LOAD	OUTPUT VOLTS	OUTPUT kW	OUTPUT kVA	OUTPUT PF	OUTPUT THD	DC VOLTS	DC AMPS	DC WATTS	PRIMARY AMPS	EFFICIENCY
No load	243	-	-	-	3.0%	127	0.6	0.076	7.9	-
2kW resistive	242	1.9	1.9	1.0	2.4%	124	16.9	2.096	29.3	92.10
4kW resistive	240	4.0	4.0	1.0	3.0%	122	35.5	4.331	57.5	92.36
6kW resistive	240	6.0	6.0	1.0	3.6%	120	56	6.720	86.0	89.29
8kW resistive	240	7.7	7.7	1.0	3.9%	118	75	8.850	112.0	87.01
Air conditioner	239	0.77	1.12	0.69	3.1%	124	7	0.868	13.4	88.71
Air conditioner plus 2 motors	238	1.06	1.93	0.56	4.5%	124	9.6	1.190	24.0	89.05
Air conditioner plus 2 motors plus 2kW	238	3.00	3.40	0.98	3.2%	122	26.4	3.221	46.0	93.14
Fluorescent bank	240	0.30	0.59	0.51	2.8%	125	2.7	0.338	5.2	88.89
Fluorescent bank and 2kW resistive	240	2.17	2.22	0.98	2.8%	123	19	2.337	32.0	92.85
Fluor bank, a/c plus 2 motors	236	1.33	2.45	0.54	4.8%	124	12	1.488	31.0	89.38
Capacitor bank (120uF)	249	0.03	2.48	0.01	8.8%	125	2.4	0.300	41.0	10.00
Heat gun on 50% power (half wave current)	242	0.77	0.84	0.91	4.7%	124	7.0	0.868	15.3	88.71

Table 3.2 Existing analog inverter control electronics performance test.

Program 3 : Hybrid Control System (Task 2)

4.0 Introduction

This program addresses the development of software and hardware which facilitates system-level communications and control of the PV-hybrid and grid-interactive stations. This program included :

- Research into resource dispatch strategies to develop new control algorithms
- Development of 'C' replacement code for existing software modules
- Development of a MOD-BUS communications protocol module
- Development of enhanced logging structures for improved fault tracking
- Integration of an enhanced software data logging module
- Incorporation of hardware designed extended memory addressing

The scope of work for task two and the associated milestones were comprehensive. The division of the task into two separate programs sought to simplify management of this task. Task two comprised both a systems control component, dealing mainly with the hybrid control system and associated algorithms, and second, an operational monitoring capability remote from the control system. The latter component required the definition of communications media, protocols and human interfaces. Section 6.0 addresses this sub-task directly.

The existing Hybrid Station Controller (HCS) design was limited to 32 kilobytes of data RAM and 32 kilobytes of program ROM. This capacity reflects the typical storage limitation of low-cost micro-controllers being 64 kilobytes of combined ROM and RAM.

In this application the control system algorithms have become very comprehensive and require program storage exceeding the 64Kbyte limit. Further, market research has indicated that internal storage capabilities should provide over one months data history, again exceeding the 64K limit.

Prior software development and hardware design required that the micro-controller and hardware configuration be standard. This limiting factor posed a technical challenge which was solved by implementing a technique known as memory banking. This is achieved by designing the software to present 64K segmented "chunks" of the control program to the controller when necessary. The hardware modifications required interfacing of the control software to the enhanced ROM and RAM components enabling the required program "chunk" when requested. The new design now implements a banked memory arrangement, allowing 128 kilobytes of RAM and 128 kilobytes of program ROM. The result is extended data log storage exceeding one month at 15 minute intervals and full integration of the operator interface into the main controller, eliminating the need for a separate interface card for smaller controller systems.

4.1 Accomplishments

The scope of hybrid control system research is vast. Investigation moved from research regarding optimal dispatch theory to the review of currently implemented dispatch strategies and available tools to support control system development and simulation.

AES Ltd. in Australia has an existing control PLC for commercial hybrid applications. Analysis of the strengths and weaknesses in the dispatch algorithm of this product were of key importance in proposing a revised PV-hybrid control algorithm. The following list details some significant work undertaken thus far.

- Review of economic analysis models and principles, the objective here was to identify if any significant life-cycle cost reductions were achievable.
- Investigation of effects in supply side management and demand side management
- Conversion of existing hybrid control software from assembly code to 'C' code.
 1. Complete change of the internal message passing protocol supporting
 2. Enhanced system time-keeping software module for improved monitoring accuracy
- Enhancement of the integrated data logger design while maintaining compatibility with existing hardware.
- Development of new code modules which interface to the kemal system.
- Development of new operator interface capabilities, including the conversion of existing assembler code and extension of functionality with the introduction of multi-lingual version.

4.2 Milestone m -1.3.2 Review

This milestone details the preliminary definition of communications algorithms and control protocol. The results of this program impact directly upon milestone m-1.3.2. The following are achievements from this program directly satisfying the milestone.

- Time-series algorithm identified as the most practical for near-term commercial implementation
- Proposed improvements to the sensing of system parameters to improve existing dispatch strategies
 1. Battery State of Charge monitoring using Kinetic model for implementation
 2. Enhanced design of the logging system to support more complex point sensing
- Definition of the Modicon MOD-BUS protocol for communications between the control system RTU and other management controllers.

- Development of a preliminary MOD-BUS register map to interface to existing station implementations.
- Completion of a MOD-BUS software module to support communications between a PC and the control system.

4.3 Milestone m-1.4.2 Review

Communications protocol definition and implementation

Control system implementation

The milestone details the completion of the control algorithms. This milestone marked the completion of software developed for the integrated software control card (ICC) and also software supporting the bank switching memory system.

As discussed earlier, the scope of control software development has exceeded resourcing given the time constraints. However, the synergies in code requirements between the PV-hybrid and grid-interactive unit dictate some degree of over-lap between phase one and phase two. Resource control software has been the focus of development. The software design of this component is shown in figure 4.1.

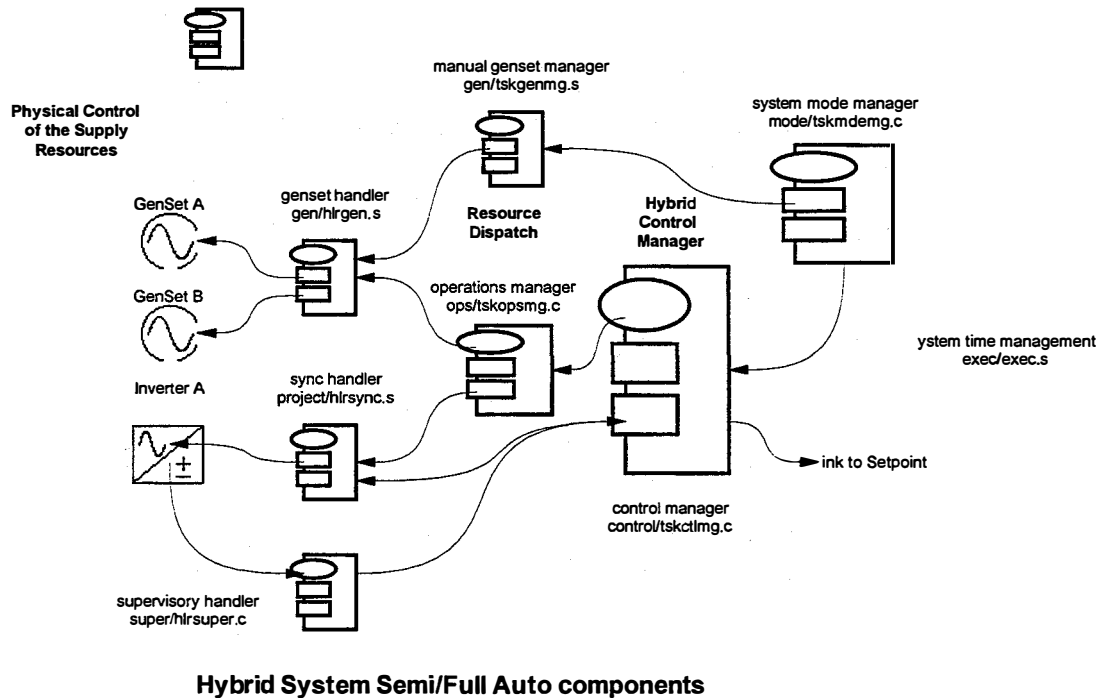


Figure 4.1 Design of resource control software modules.

To complete this milestone the station support software modules must first be completed. Again, these modules pertain to both products. The second task is the implementation of the reviewed algorithms to realize the unique control module supporting PV-hybrid operation.

4.4 Discussion

The definition and implementation of the communications software modules and remote control interface is considered complete within the scope of phase one. The development of PV-hybrid station control software is still however under development.

Significant progress is anticipated during the test period outlined in phase two of the program. Thus far, testing has been carried out on a small scale simulator. Unit testing will provide a unique opportunity to optimize and de-bug the system software while operational within the prototype unit.

Modules developed so far include :

1. Time keeping module
 - supporting real-time clock and generation of time-date stamps for event logging
2. Generator / Grid resource control module
 - controlling start, stop, connect and disconnect control of AC sources
3. Synchronizer module
 - controls the frequency, phase and voltage lock of the inverter to AC sources
4. Operator interface module
 - supports operator control of the system via LCD and entry pad
5. User configuration module
 - supporting the definition of adjustable set-points
6. Data logging module
 - supports periodic averaging of sensing points within the control system and associated storage of data records
 - embedded database support allows simple extraction and location of data records

Rapid development and completion of the control station support software is a key objective in phase two. Final review and integration of the newly developed modules with enhanced resource control software will present a significant challenge.

Program 4 : SCADA remote monitoring system (Task 2)

5.1 Introduction

This program focused upon the development of software which facilitated the remote control and monitoring of the PV-hybrid system and is derived from the task two work statement. This program was contracted in part to Dumont Associates, a software development group specializing in MMI (Man Machine Interfacing). The program involved development of two key software modules. First, the communications module which was to support the Modicon MOD-BUS communications protocol. Second, the GUI operator interface enabling the control and monitoring of the PV-hybrid station controller.

5.2 Accomplishments

Development of a Windows 95 based "SPP-Link" package, facilitates PC-modem to PV-hybrid unit communications included the following activities :

- Development of draft specifications for graphical layout and icon design (m-1.3.2)
- Development of MOD-BUS interface, now defunct and replaced by third-party OCX
- Development of a DLL for data conversion between the OCX and MMI software
- Development of Visual Basic Operator interface
- Unique definition of a site database within MS-Access facilitating complex data queries
- Development of hybrid specific graphical icons and powerful operator package with programmable levels operating ability

This enhanced package makes extensive use of windows graphics, communications and provides a user friendly control environment. The SPP-Link remote operator package interfaces the hybrid SCADA system with an MS-Access database and will automatically load remote historic performance information into a unique site database. Site operation can now be reviewed and analyzed using automated database queries. This significantly reduces the labor required to monitor and make informed recommendations regarding remote systems performance.

5.3 Milestone m-1.4.2 Review

Control system implementation

Communications protocol definition and implementation

The protocol chosen for system communications was the Modicon MOD-BUS protocol. This protocol is widely used in PLC control systems and has excellent third party driver support. The protocol has inbuilt error checking, send-acknowledge type operation well suited to data polling of sensing points within the control system. The ability to set and clear data within registers allows remote configuration of control parameters.

To facilitate communications with a PC-modem a third-party MOD-BUS OCX was implemented between the PC MMI and RTU. Within the PV-hybrid control system a MOD-BUS driver was developed to communicate via RS-232 connection and over modem link. The remote monitoring package allows a remote operator to access a variety of control and data logging pages.

1. System control page

- Selectable manual, semi-automatic or fully automatic operating modes

2. Operational overview page

- Displays system resources and relevant operating parameters such as power, voltage and current output and fault status
- Display of real-time data in graphical trend forms, with the ability to scroll back to review recent past performance data

3. Configuration page

- System, resource and control parameters can be modified or reviewed
- Password protection ensures that unauthorized users are locked from making system modifications

4. Alarms page

- Displays any system alarms in chronological order, common fault sequences can be rapidly identified and therefore remedied

5. Connect page

- The connect page links the package to the specific database and particular site to be interrogated. Site information, contact names and system resource specifications are stored within this page

5.4 Discussion

The ability to remotely operate or interrogate a station provides the product distributor or support group an opportunity to investigate faults and performance glitches without physically visiting the installation. Typically, site visits incur high costs, the more remote the site the higher the cost. The interface package developed extracts detailed operating information from the station controller and greatly assists in fault diagnosis. In some cases, where skilled operators are not locally available remote operation becomes mandatory.

The package developed in phase one has direct application to control parameters and sensing points within the PV-hybrid prototype. Phase two will enhance the package further for compatibility with three phase PV-hybrid and grid-interactive station controllers.

Program 5 : Prototype Design and Manufacture (Task 3, 4)

6.1 Introduction

A key objective of the PV-MaT 4A contract was the design and development of a high quality product for US manufacture and establishment of a local manufacturing partnership. To this end, a manufacturing collaboration was developed between AES Inc. and WPI Power Systems.

The issue of long term alliance has been discussed with WPI with a positive outlook. Both parties have contributed greatly toward achieving a successful pilot manufacturing program. Development of substantial manufacturing documentation was considered key to realizing a reliable and repeatable product. The ability to draw on WPI's experience in low-medium volume, power electronic system's manufacture has already proven to have been of significant advantage over other manufacturing options. To this end, the prototype manufacture has been successful.

6.2 Accomplishments

Key achievements completed to date include.

- Modular design of the IGBT power switching sub-assembly, "Power-Block"
- Product Bill of Materials in MS-Access Data Base with Customized Queries
- Magnetic components designed, manufactured and tested locally at WPI
- Development of prototype 20 kVA single phase power test unit
- Completed electrical specifications and CAD drawings of prototype unit
- 60 kVA prototype PV-hybrid system production at WPI Power Systems completed

6.3 Milestone m-1.3.3(1) and m-1.3.4

This milestone details the completed design of the prototype PV-Hybrid.

To complete the design of the prototype unit the system components were reviewed with the view to reduce the overall cost of the system. The preliminary design was decomposed into three distinct sub-assemblies whereby each could be built and possibly replaced in a component-like fashion, primarily to simplify its manufacture.

- 1) *Enclosure and Output Stage*, this encompasses the mounted output transformers, inductors and the cabinet.
- 2) *Power Block*, this combines the IGBT devices, drivers, capacitors and bus work mounted upon a single heat sink assembly. This component is replicated for each phase. This design has positive benefits for both field servicing and pre-installation test and performance verification.

- 3) *Electrical Looms & Control Harness*, this includes the wiring of connections between sensing and control points. The control system and switch gear enclosure is mounted along side of the primary inverter enclosure.

6.4 Manufacturing Package

Following the definition of these components detailed CAD drawings were developed to support the new designs. AES worked closely with WPI to establish the necessary documentation to move into manufacture. The final pre-production package consisted of the below items.

- Comprehensive Bill Of Materials
 - Component data sheets
 - Component cut sheets, defining dimensions and mounts
 - Component primary and secondary sources
 - Component pricing
- CAD drawings of the PV-Hybrid system
 - Hybrid enclosure : inverter, control system, switch-gear housing
 - Inverter electrical connection diagrams and terminal allocations
 - Inverter power module drawings with heat-sink assemblies
 - AC resource switching schematics and layout drawings
 - Control system schematics and layout drawings
- Cable definitions, cable sizing, connection types, wire sizes and colors
- Specific assembly instructions

This milestone contributed significantly to deliverable D-1.2. The pre-construction manufacturing specification.

6.5 Milestone m-1.4.1

This milestone details the assembly of the prototype. It is important to note that this milestone underwent a minor change in definition as it became apparent that manufacture of the full three-phase prototype unit would be delayed. The construction of a single phase power test prototype became necessary to eliminate any delay in the verification of the new inverter topology, pre-empting potential problems with the final design. Any shortcomings in the design could then be rectified in the final prototype construction. The construction of the prototype assisted in the following ways.

- Verification of component selection
- Verification of magnetic components
- Verification of inverter control electronics and power drive stage

- Verification of power switching topology
- Facilitate performance comparison between new and old control electronics

The prototype underwent tests to determine inverter performance using a variety of electrical loads. The objective here was verification of performance criteria as defined by the initial specification using modified magnetic components designed and built by WPI. Thus far minor issues have arisen, however, these were not considered to affect performance dramatically.

To assist in the completion of this milestone AES Inc. in conjunction with AES Australia developed a parts list which detailed bill of material parts which must be supplied from AES group. A clear objective was to minimize the components required from AES Group. To this end, over 90% of the Bill of Materials was sourced directly by the manufacturer. Components supplied by AES Group were the PV-MaT developed control boards and specific interface equipment. These were small components and easily bench testable. This translates to a clear message, in partnering with a semi-custom manufacturer the business operating model becomes “lean” by dramatically reducing the requirement for costly overheads in attempting to directly support manufacture activities and carry inventory.

6.6 Milestone m-1.4.4 Cost Analysis

This milestone details the completed assembly of the deliverable prototype.

The manufacturing of the inverter unit was completed late February 1997. The objective of the manufacturing process was two fold. First, to meet the functional operating objectives as posed in the initial specification. Second, to achieve the cost projections through component rationalization and local manufacture with a medium scale operation. The PV-Hybrid cost has been analyzed in three components, control, AC-switch-board, and inverter. The table below describes the hybrid control system cost break-down.

Component	Qty	Cost per item	PART#	Total
SCM - 3 phase	1	\$250		\$250
CPU Module	1	\$255		\$255
SIM - 3 phase	1	\$400		\$400
DISPLAY-PCB	1	\$150		\$150
LCD & PANEL	1	\$90 + \$170		\$260
MODEM	1	\$150		\$150
PSU AC-DC	1	\$150		\$150
PSU DC-DC	1	\$95		\$95
Station Battery (24V)	2	\$90		\$180
Connectors & Misc	1	\$100		\$100
Component Total				\$1890
Labor	16	\$15		\$240
Total				\$2230.00

Inverter sub-assembly breakdown

Component	Qty	Cost per item	PART#	Total
IGBT	6	\$262.00		\$1572.00
XFRM	3	\$1333		\$3999.00
L-HF	3	\$315		\$945.00
L-LF	3	\$504		\$1512.00
HSink	3	\$204(Q10)		\$612.00
DC-Cap	6	\$55(Q10)		\$330.00
AC-Cap	6	\$44.50		\$267.00
AC-FiltCap	3	\$15		\$45.00
IGBT-Drive	6	\$216.00		\$1296.00
Overload CTs	3	\$0	TBF	\$0.00
3PHS-Cont	1	\$350.00		\$350.00
Cabinet	0.8	\$1200.00		\$960.00
Cu Buss	1	\$150.00		\$150.00
Connects	n/a	\$100.00		\$100.00
Component Total			\$12138.00	
Labor	48	\$15		\$720.00
Component and Labor Total		\$12,858		
DC Breaker	1		\$1500.00	\$1500.00
Total				\$14358.00

Summary ratio at 60kW yields \$24 cents per watt for the inverter sub-assembly

AC-switch-components breakdown

Component	Qty	Cost per item	PART#	Total
Inverter Breaker	1	\$472	QSB23175L	\$472
Genset Breaker	1	\$472	QSB23175L	\$472
Inverter Contact	1	\$1500		\$1500
Genset Contact	1	\$1500		\$1500
Relays 24 Volt 2PDT	7	\$20		\$140
Relays 24 Volt 3PDT	2	\$25		\$50
Buttons & Switches	3	\$50		\$150
Cabinet	0.2			\$240.00
Connects & Wiring Misc.	1	\$200		\$200.00
Component Total				\$4724.00
Labor	16	\$15		\$240.00
Total				\$4964.00

Cost Summary

The general breakdown of the SPP into sub-assemblies of the inverter, control and monitoring and AC-switching yields the following.

60kVA Inverter sub assembly	25 cents per Watt (33 AUS cents per Watt)
Control & Monitoring sub assembly	3.7 cents per Watt (5 AUS cents per Watt)
AC switching components	8.2 cents per Watt (11 AUS cents per Watt)
Total PV Hybrid Cost	37 cents per Watt (49.2 AUS cents per Watt)

Points of interest

- All calculations were based on the “as-built” bill-of-materials NOT on volume costs.
- This cost break-down does not include the non-recurring engineering fees.
- Costing of the Inverter sub-assembly and hybrid control components are within 5%.
- Exact component costs are not available on items purchased by WPI, non-recurring engineering fees, components, cabinet, manufacture and assembly was invoiced at \$34k Cost share removed from calculation.
- Cabinet cost is yet to be determined exactly and is based on the indirect calculation from WPI invoices.
- Actual costs attributed to WPI build total approximately \$22,500. This consists of \$16,820 basic manufacture, assembly and test costs to WPI and the AES supplied components at approximately \$5,400. This produces a cost per watt at 37 cents. This verifies the above tables.

6.7 Discussion

Key achievements completed to date are detailed below.

Achievement of the manufacturing cost objectives for the inverter component and the PV-MaT PV-Hybrid. The aims were for \$0.30 / kW for the inverter component, and \$0.45 / kW for the PV-hybrid unit. The achievements were shown as \$0.24 / kW for the inverter component and \$0.37 / kW for the PV-Hybrid.

Development of the first revision “power block” concept. Although still in the prototype stage, the concept of a removable component which is simple to install and also replace provides significant advantages in cases of field failure and servicing.

The power block contains the IGBT devices mounted upon a heat-sink block with pre-calibrated IGBT drive cards. The potential exists to assemble, configure, power test and verify operation of the most failure prone, and most critical inverter sub-assembly.

Currently, IGBT failure requires that a qualified technician remove failed IGBT devices from fixed heat-sink assemblies. Once replaced, testing must be undertaken in-situ. If the inverter unit can not be isolated to a load bank burn-in tests must be carried out using the village load. This is cumbersome and undesirable as village load is typically unpredictable. Many secondary failures can occur in this manner.

Replacement of pre-tested assemblies removes the need for field burn-in and also reduces the skill level required for the ground support personnel.

It is proposed that a similar power block topology be refined for use in phase two within the grid interactive design.

The innovations which enabled the integration of the inverter control into a single PC have dramatically simplified the construction and lay-out of the PV-Hybrid. The number of component interconnections has been dramatically reduced. This impacts positively upon time required to assemble the end product. Further, set-up of the unit is to some degree automatic in that external set-up jumpers were previously. This is no longer a requirement with much the set-up internal and implicit in the installation. The "Power-Block" approach extends this same principal into the power electronics components.

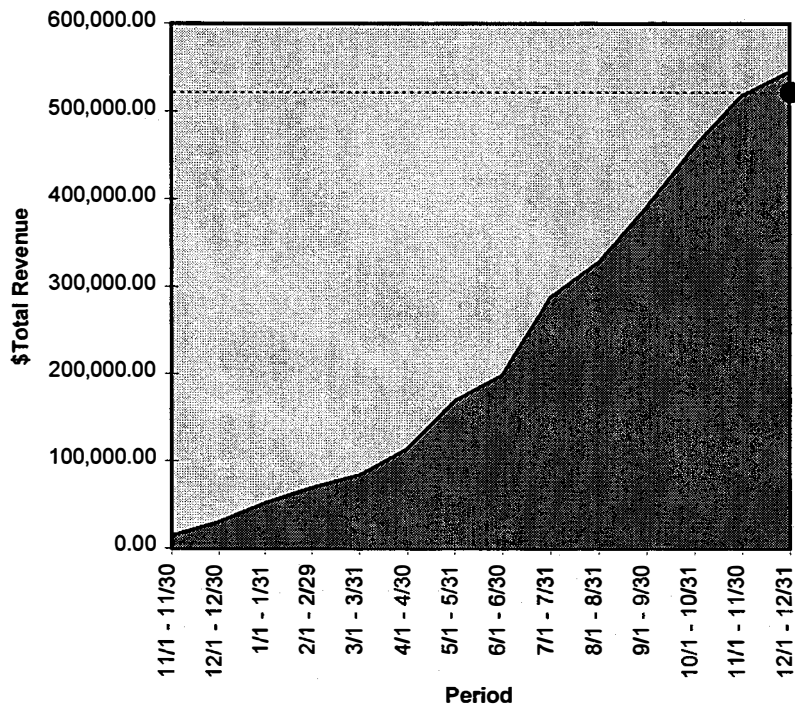
The documentation completed in phase one for the PV-hybrid relates strongly to that required for the phase two unit. A significant proportion of the materials bill, CAD diagrams and electrical layouts will be pertinent to the PV-grid prototype manufacture.

7.0 Phase one budget review

7.1 Introduction

The phase one program successfully achieved a significant percentage of the proposed objectives. The final expenditure as of December 31st, 1996 was over budget by approximately \$17k. This constitutes a 3-4% budget overrun.

Phase one expenditure



7.2 Discussion

Two issues regarding the budget need addressing. First, the status of phase one tasks and percentage completion. Second, the impact on the phase two budget due to over spending.

All phase one tasks, with the exception of task 2, were 100% complete by February 28th. Task 2 was identified in the introduction as incorporating significant control system software development. As discussed, the software synergies between PV-hybrid and grid-interactive deliverables negates the significance of this development overrun.

The overspend can be contributed to software development costs and within the scope of the entire project is considered marginal at 3.5%. This expense has been incorporated into the revised phase two program.

8.0 Phase Two Review

8.1 Introduction

Phase two begins on 15th of January 1997. The clear objective for phase two is delivery of the fully tested and fully functional PV-hybrid to NREL. The following objectives are considered critical in phase two.

- Test and verification of the PV-Hybrid at Sandia Laboratories
- Application of the PV-Hybrid at the Wind-Test site at NREL Facilities
- Consolidation of phase one developed inverter technology into a fully featured, well packaged product
- Design and development of a Grid interactive (PV grid) inverter
- Repeatable manufacture capability of standard product options
- Highest reliability, lowest cost product

To achieve these objectives, further development will continue into support software and of application-specific control algorithms (PV-hybrid and grid-interactive). Remote monitoring software will be developed for the grid-interactive unit based on the PV-hybrid package. Further collaboration with WPI Power will continue to develop and refine the production documentation and generate material for the manufacture of the grid-interactive prototype unit.

The reduction in funding for completion of the phase two program has impacted the rate at which the original milestones can be achieved. A revised schedule has been defined and is discussed below.

8.2 Original milestones of phase two

The milestones listed below were outlined as phase two objectives.

- m-2.1.1 Complete PV-hybrid inverter testing at AESI
- m-2.1.2 Complete PV-hybrid testing at Sandia National Labs.
- m-2.1.3 Complete testing at NREL wind test site.
- m-2.2.1 Complete design of UI inverter, drawings and mechanical layouts.
- m-2.2.2 Complete draft O & M manual for the PV-hybrid
- m-2.2.3 Complete system specification for UI inverter.
- m-2.2.4 Complete Task#5. Test and evaluation of PV-hybrid.
- m-2.2.5 Complete Task#6. Complete UI design documentation.
- m-2.3.1 Complete Assembly of the prototype.
- m-2.4.1 Complete Task#7. UI prototype construction.
- m-2.4.2 Complete definition of the product models, manufacturing plans and costings.
- m-2.4.3 Complete Task#9. Manufacturing planning

m-2.4.4 Complete reporting of start-up venture results and pilot manufacturing details.

m-2.4.5 Complete production of UI system.

m-2.4.6 Complete Task#8. Complete Test and evaluation of UI system.

m-2.4.7 Complete Task#10. Initiate pilot manufacture.

8.3 Phase two budget

The phase two budget has now been approved for a further \$266,235.00. The project duration and billing period has been approved from January 15th 1997 till November 1st 1997, a period of 10 months. With the new budget the average maintainable burn-rate must not exceed \$17,800.00 direct billing and \$8,900.00 per month on overhead expenditure. The income injection per month will total \$26,675.00.

This constitutes a significant reduction in projected burn-rate for phase two in comparison with phase one and in anticipated 1997 funding. This was a consideration in the revision of the phase milestones and deliverables.

8.4 Phase two deliverables

The phase two deliverables below were agreed upon by the TMT and the annual program review.

Phase II (1/15/97 - 11/1/97)

Deliverables To Be Achieved

- D2.1 Deliver prototype PV-hybrid to SNL (28 February 1997)
- D2.2 Deliver test results and O&M manual (30 May 1997)
- D2.3 Deliver prototype specification for grid-interactive product (30 November 1997)
- D2.4 Deliver production model of grid-interactive model (1 March 1998)
- D2.5 Deliver report detailing the manufacturing process and costings. (31 March 1998)
- D2.6 Deliver fully featured control software for PV-hybrid to NREL (31 July 1997)

NOTE : The deliverable dates have been modified to realistically represent the revised contract schedule. Further, D2.6 is new and requested by TMT at phase one review.

Note that Phase III is internal AES Inc. terminology only to represent a third round of funding.

Deliverables To Be Extended into Phase III

- D2.4 Deliver production model of grid-interactive model (31 March 1998)
- D2.5 Deliver report detailing the manufacturing process and costings. (31 March 1998)

Phase III (11/1/97 - 3/1/98)

Deliverables To Be Achieved

- D3.1 Deliver production model of grid-interactive model (1 March 1998)

- D3.2 Deliver report detailing the manufacturing process and costings. (31 March 1998)

Phase II & III(1/15/97 - 1/3/98) milestone projection

Milestone	Description	Completion Date
m-2.1.1	Complete PV-hybrid inverter testing at AESI (Task 5)	2/28/97
m-2.1.2	Complete shipment and on-site prep of PV-hybrid at Sandia National Labs.	3/31/97
m-2.2.1	Complete installation of PV-hybrid at NREL wind test site.	4/30/97
*** m-2.2.7	Complete the design of UI inverter, drawings and mechanical layouts.	12/31/97
m-2.2.3	Complete draft O & M manual for the PV-hybrid	5/1/97
m-2.2.4	Complete system specification for UI inverter.	10/30/97
m-2.2.5	Complete Task#5. Test and evaluation of PV-hybrid.	5/1/97
m-2.2.6	Complete Task#6. Complete UI design documentation.	1/31/98
m-2.3.1	Complete Assembly of the UI inverter prototype.	1/31/98
m-2.3.2	Complete Task#7. UI prototype construction.	2/15/98
m-2.4.1	Complete GI prototype testing atAESI.	3/1/98
m-2.4.2	Complete definition of the product models, manufacturing plans and estimates for high volume and pilot manufacture.	10/30/97
m-2.4.3	Complete Task#9. Manufacturing planning	10/30/97
m-2.4.4	Complete reporting of start-up venture results and pilot manufacturing details.	3/31/98
m-2.4.5	Complete production of UI system.	3/1/98
m-2.4.6	Complete Task#8. Complete Test and evaluation of UI system.	3/31/98
m-2.4.7	Complete Task#10. Initiate pilot manufacture.	3/31/98

Attachments

There are no attachments

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (<i>Maximum 200 words</i>) This report describes the accomplishments of Advanced Energy Systems Inc., under Phase One of their PV Manufacturing Technology (PVMaT) subcontract. These accomplishments include the development of hardware, software, product documentation, and capabilities and specifications for a PV-hybrid three-phase inverter. The document defines models, performance, electrical, and physical system parameters; enhanced control system, liquid-crystal display interface providing intuitive, multi-lingual operator support; integrated high-precision data and event-logging capability; development of Windows-based system control and data acquisition software for remote monitoring; significant integration and simplification of the inverter control card electronics; enhanced performance of sinewave generation that exceeds market requirements for PV-hybrid "village application" voltage regulation parameters; implementation of digital control core facilitating further development of integrated self-test and diagnostic procedures; compilation of comprehensive Bill of Materials with data sheets for the PV-hybrid product; development of specifications and production ability for magnetic components in the inverter; collaboration with WPI Power as a semi-custom manufacturing group; and development of a single-phase test inverter leg for high-power performance and design evaluation.			
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