NREL/SR-520-23401 • UC Category: 1280

Development of a Modular, Bi-Directional Power Inverter for Photovoltaic Applications

Annual Technical Progress Report August 1995 - August 1996

C. Freitas
Trace Engineering Company, Inc.
Arlington, Washington

NREL technical monitor: H. Thomas

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

Prepared under Subcontract No. ZAF-4-14271-08

August 1997

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (423) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

CONTENTS

PHASE I ANNUAL PROGRESS REPORT

PVMaT Subcontract: ZAF-4-14271-08

Subcontractor: Trace Engineering Company, Inc.

Subcontract Title: Modular, Bi-Directional Power Inverter for Photovoltaic Applications

Reporting Period: August 1995 to August 1996

1.0 EXECUTIVE SUMMARY

The goal of this research and development contract is to develop and prototype for manufacturing a modular, bi-directional power inverter for photovoltaic applications. This modular inverter will be used as a building block for larger inverters by connecting in parallel (for higher power) or in series (for higher AC voltage) or both. The modular inverter will be capable of being interconnected for single, split and three phase configurations for both 60 hertz (domestic) and 50 hertz (international) applications. The design will also allow construction of units with different DC input voltages and AC output voltages to further satisfy various application and market requirements.

By standardizing on a single "building block" inverter module, the need to build multiple models and sizes for different applications can be avoided. The higher volume of a single design will allow improved manufacturing and will result in higher reliability by reducing low volume modifications. The result will be lower cost and improved performance of photovoltaic systems.

Achievements: During the first year (Phase I) of this research and development effort, the following work was completed:

- Conducted a review of possible inverter designs and identified preferable approaches.
- Developed and built initial "breadboard" prototypes of two different inverter designs.
- Evaluated the performance through computer modeling and laboratory testing.
- Selected one of the two designs for further development into a manufacturable prototype.
- Refined the design to reduce no load power consumption. Reduced the consumption from 30 watts to less than 10 watts for a 2kW power inverter module.
- Developed an advanced hardware based protection system for the MOSFET transistors.
- Built a manufacturing prototype of the selected design using production methods and materials. The prototype was built up in an existing product chassis to emphasize the compatibility of the design with current production methods and components.
- Demonstrated the final Phase I prototype to the PVMaT subcontract monitors Holly Thomas, Ward Bower and Ben Kropowski at the annual review meeting held at Trace Engineering in August of 1996.
- Submitted the final Phase I prototype to Sandia National Laboratories for additional testing.

Impact of Results: The benefits of the building block approach for power inverters used in photovoltaic applications include:

- **Reduced cost** - the modular inverter can be built in greater volume using more advanced production methods. The single design will allow for greater investments in the production and test equipment since fewer different models will be built.
- **Improved performance** - the modular inverter can be custom "fitted" to the application, reducing oversizing which causes poor efficiency of the photovoltaic system.
- **Improved reliability** - the modular inverter can be designed to allow for N+1 redundancy and hot swappability. This reduces the impact of a single inverter module failure or shutdown.

This research and development contract also has had several side benefits for Trace Engineering:

- Adaptation of the newly developed hardware based protection circuit was completed for our existing DR and SW series product lines. This circuit was phased into production starting in April of 1997. The circuit adds another level of protection to the two methods already included. Initial results show a substantial improvement in both the factory yields and a reductions of the in-field failures.
- Development of a "new concept" product called the CO-sine inverter outside of this contract. This product used much of the technology developed for the original prototype. The CO-sine is intended to accept any AC waveform or frequency and provide a ultra low distortion AC sinewave output for small sensitive loads such as test equipment, audio-video gear etc. The product was completed to the production prototype level and 25 BETA units have been fielded. Feedback from the BETA testing verified the product potential, but also identified significant problems requiring attention before the product could be mass produced and sold. This new product is currently on hold pending the availability of additional engineering resources required to complete it.

The progress of this research and development contract was delayed at the end of the Phase I period by the loss of one of the primary engineers, Milt Rice, in a plane accident. Milt made many important contributions to this project and will be very difficult to replace. We are fortunate that he was able to see many of his ideas become a reality during the time he spent on this project.

2.0 INTRODUCTION

This annual report focuses on the first year (Phase I) of the development of a modular, bi-directional power inverter for photovoltaic applications by Trace Engineering Company, Inc. of Arlington, Washington. This development has been conducted under the PVMaT Phase 4A1 program. The reporting period is from August 1996 to August of 1997.

Trace Engineering has been manufacturing power inverters for over 12 years and has built more than 250,000 inverters. The majority of the inverters built have been used in renewable energy applications. Until recently, Trace concentrated on the stand-alone, non-utility interactive applications. With the introduction of the Trace SW series in 1994, Trace expanded its product line into utility interactive and larger hybrid system applications. Trace Engineering is now the largest manufacturer of inverters for photovoltaic applications in the world.

The increased production volume and expansion of the Trace product line into numerous models and power levels to meet the requirements of the wide range of possible applications caused Trace to see the need for the development of new inverter designs which could be manufactured more easily, used more flexibly in different applications, and which could achieve higher performance and reliability. This PVMaT subcontract has provided the needed impetus to accelerate those efforts through the development of a modular, bi-directional power inverter which could be used as a "building block" for larger and more complex systems. The modular inverter is expected to fill the requirements for stand-alone, hybrid and utility interactive applications by connecting them in parallel (for higher power), in series (for higher AC voltages) and in single phase, split phase and three phase configurations.

3.0 OBJECTIVES

The overall objective of this research and development contract is to "Develop and prototype for manufacturing a modular DC to AC power inverter for photovoltaic applications". This is to be achieved developing a inverter which:

- Achieves cost reductions
- Increases modularity to allow easier expandability and improved servicing
- Attains higher efficiency
- Increases the power density to reduce the size of the module
- Expands the abilities to allow one design to be used by more market segments
- Improves the reliability of photovoltaic systems through redundancy of the modular inverters
- Increases the adaptability of the inverter system design to unknown application requirements

Phase I objectives are limited to the development of the modular inverter itself, while Phase II will handle the further development of the modular inverter system including the fault tolerance, parallelability and control as a group for larger inverter systems.

4.0 SCOPE OF WORK

This research and development completed under this contract will result in a modular, bi-directional power inverter which has the following improvements and characteristics:

1. Reduced cost over existing technologies

The original proposal for this contract had listed as a goal to reach a price point of 0.35 $/watt in 1997 (at the volume wholesale level - 1000+ volume pricing) for a inverter which includes required additional components such as outdoor enclosure, ground fault protection, disconnects required for an application such as utility connection.

This goal seems achievable - Trace recently sold SMUD approximately 80 inverters with the listed additional components for about 0.43 $ watt based on the existing SW5548UPV (5.5-kW) utility interactive sinewave inverter. Achieving SMUDs stated goal of 0.15 $/watt for the residential sized (4 to 6-kW) in the year 2000 will require substantial market development (for greater volume) and continued inverter development. Through higher efficiency, a simpler design and improved manufacturing methods, the cost goals can be achieved.

The inverter developed under the Phase I portion of this contract includes several cost reducing design features. It uses a single transistor bridge, single power transformer and single microprocessor instead of the currently produced SW series inverter's three microprocessors, three power transformers and three transistor bridges. It also is more compact, reducing the chassis and enclosure cost. The smaller 2-kW size will also result in higher production volumes, reducing cost further.

2. Improved power density

The 2-kW inverter module uses a simpler and more efficient power layout compared to the currently produced SW series inverter. Overall volume has been reduced by approximately 15% per kW of continuous rating compared to our current SW series design. The design also resulted in approximately 30% lower weight by improvements in transformer material utilization and a smaller chassis size.

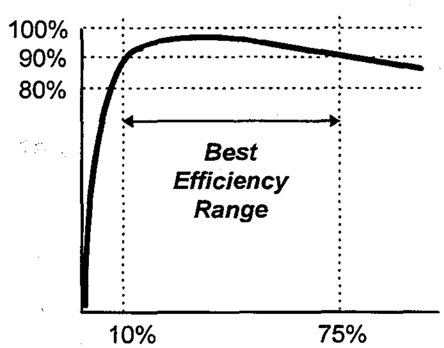
3. Modularity to allow easier expandability and adaptability

The 2-kW inverter module is designed from the start to allow use in either parallel or series combinations to meet a wide variety of capacity and system configuration requirements. This design is also easier to adapt from 60 Hz to 50 Hz for export markets. The ideas developed to allow the parallel and series operation for the modular inverter are also being adapted to Trace's currently produced SW series of inverters to better enable accelerated development and to possibly apply the concept earlier using the existing SW series inverter as an initial "modular inverter".

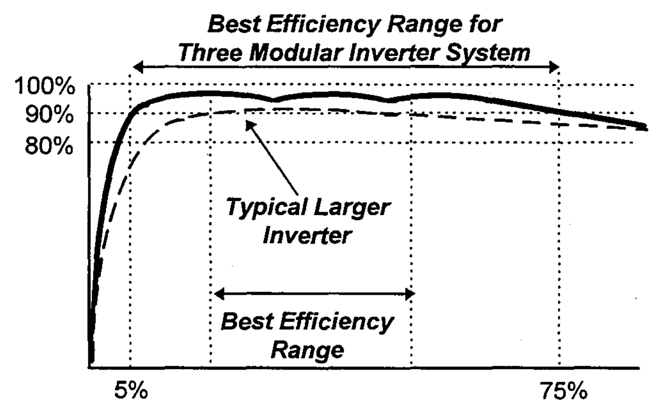
4. Improved efficiency ✓

The improvements in the efficiency are primarily achieved in the operation of the inverter modules and not in the inverter module itself. The inverter module is being designed to have extremely low idle power consumption and good high power efficiency. The use of smaller inverter modules reduces the losses since less current has to be handle through a single component (using two 2-kW modules compared to a single 4-kW inverter, for example).

The inverter system can also turn off the unnecessary inverter modules when they are not required by the system loads to further reduce the idle losses and improve the low load system efficiency. The inverter modules can be turned on one at a time to maximize the inverter system's efficiency by keeping the operating point on the efficiency curve near the peak region for each operating module. This results in an efficiency curve as follows:



Single Modular Inverter Efficiency Curve



Three Module Inverter System Efficiency Curve

The best efficiency range shown is when the inverter operates at over 90% efficiency. As shown, the inverter system using three modular inverters reaches high efficiency very quickly and remains at high efficiency for an extended range. As a comparison, a typical larger efficiency curve is shown for more conventional inverter technologies.

The improved efficiency is achieved by turning off the modular inverters that are not required to handle the AC loads connected. At very low power levels, only a single modular inverter operates. As the AC loads increase, the modular inverters are turned on to maximize the efficiency of the system.

This advanced system operation is not required if the application has a significant base load which is powered all of the time. It is most beneficial for residential systems and some types of commercial system, such as resorts or offices.

5. Improved reliability

Improved reliability will be achieved by simpler design and the use of better protection systems. The 2-kW inverter module uses about 1/3 the parts of the 4-kW SW series inverter design. It also includes a unique protection system on the DC side of the inverter to protect the MOSFET transistors from damage during faults or problems. This system can be included at very little additional cost and provides the same protection as systems which was previously determined to be too expensive to include.

This electronic overcurrent protection system has been developed and tested successfully on the 2-kW inverter module and is currently being adapted to the existing SW and DR series product lines. Our evaluation of this "spin-off" improvement suggest that this additional circuitry will improve the product reliability substantially.

The modular inverter design also allows redundancy in the inverter system by using one more inverter module than required for the load being powered. If a problem occurs in the inverter system, the faulted module can shut off and even be removed without disrupting the inverter system or loads. This is often referred to as "N + 1" redundancy and is common in the telecommunication and computer industry for DC power supplies. This feature has been offered on some inverter by other companies, but never at a competitive price or in a bi-directional inverter/charger type product.

The redundancy and hot swappability features that are being developed for the 2-kW modular inverter are also being considered for implementation in the SW series based modular inverter system. This ability is being developed as part of the Phase II section of the contract.

4.1 TASKS PHASE I - FIRST YEAR

Work on Phase I of this contract was started in August of 1995 and was completed in August of 1996.

3.1 TASK 1 - INVERTER TOPOLOGY DESIGN AND VERIFICATION

3.1.1 Subtask 1.1 - Selection of topology

The development process of the inverter module involved several starts, stops and detours. Two separate inverter designs were considered and completed to the working prototype level.

1. The original design was based on a pure high frequency topology. This design was prototyped and successfully tested to power loads up to 1 kW. The design was abandoned for several reasons. The most significant problem was excessively high no load or idle power consumption. The 1-kW prototype required over 20 watts of DC power to produce an AC output. This is almost four times our design goal. Another problem was it required expensive design features and components to allow intermittent operation at high "surge" power levels required to start motors.
2. The development effort was then concentrated on a mixed high and low (hybrid) frequency topology - which uses a high frequency power transistor bridge and a low frequency transformer. This design has been used by several manufacturers but other designs inherently have suffered from high idle power draw of more than twice our design goals at the 2-kW power level.

The original inverter design was developed, built and tested by the primary project engineer, Roger Rosenbaum. Trace then hired another experienced engineer, Milt Rice, to assist Roger with the refinement of his approach. With the switch to the hybrid inverter topology, Milt became the primary project engineer and Roger was reassigned to other projects since Milt was much more experienced with the hybrid topology and Roger was needed for other projects. Roger continued to be involved for much of the testing portions of the project.

3.1.2 Subtask 1.2 - Design initial prototype and estimate operating limitations

Several initial prototypes were constructed and used to estimate operating limitations. The transformer characteristics were developed from testing completed on these initial prototypes. Both the high frequency and the high & low frequency hybrid inverters were prototyped initially to the level of operating several hundred watts.

The power testing of the original high frequency prototype resulted in the discovery of the final flaw in the design which caused us to switch to the hybrid topology. When the high frequency topology is developed to be bi-directional, the protection required to prevent failure of the inverter was found to be very difficult to design and is expensive to implement. This is further compounded once the inverter is required to allow high power intermittent operation. This problem resulted in changing the modular inverter development effort to the simpler hybrid topology.

The output stage of the high frequency topology was further developed into a new type of inverter product. The circuit was modified to allow AC as the input instead of DC power. The AC is rectified into high voltage DC and the inverted back into DC power with the output stage of the high frequency inverter. This allow use of sensitive electronics on poor quality AC sources such as generators, modified square wave inverters and utility grids in developing countries.

This new product has been named the "CO-sine" inverter and was demonstrated at the SOLTECH 96 conference in Palm Springs, California in April of 1996. Twenty-five BETA units have been manufactured and have been sent out to various companies for testing and evaluation. This product is a direct off-shoot of this contract development effort and was expected to be potentially a significant seller. The loss of Milt Rice in an airplane accident caused us to put this product on hold until further engineering resources become available.

In the time period between the completion of the contract proposal and the end of Phase I, some of the items listed to be developed in the contract for this subtask had already been developed, implemented, and fielded in the SW series inverter product. Most of these requirements (ground fault protection, islanding, battery-less operation and maximum power point tracking for example) are included in the newly developed version of the SW series inverter designed specifically for utility interactive applications. The methods developed and components used to meet these requirements were evaluated and determined to be compatible with the hybrid topology selected for the 2-kW inverter module.

Because these requirements were well developed and are known to present no obstacles for the new modular inverter design, they were considered in the design but not implemented at this point in the development process. They will be included as in the Phase II portion of the contract as part of the final prototype development.

Some of the features have also been determined to be worth implementing on Trace's currently manufactured SW series inverter design. Several features have been tested by another Trace engineer, Greg Thomas, using the SW series inverter as a test and development bed to allow faster development and to enable the SW series inverter to be used in the immediate future as a modular inverter in a wider variety of applications. This features involved operation in parallel (for larger single phase systems) and in three phase configurations for large more complex power systems.

3.1.3 Subtask 1.3 - Build prototype of Inverter

A first complete prototype of the hybrid topology inverter core was constructed in April of 1996 by Milt Rice. The prototype was designed to fit into an existing inverter chassis used in our DR series of modified square wave inverters. This was done to reduce the development time and cost by eliminating the need for mechanical engineering and prototype drawings at this early stage. The final chassis design would be selected once the working prototypes were further developed and fully tested. Use of an existing chassis also allowed us to assemble the inverter with existing fixtures and production equipment. This is very useful during a BETA test cycle since many changes may still occur in the design after the initial field testing.

3.1.4 Subtask 1.4 - Test Prototype / Demonstrate

The prototype of the 2-kW inverter module was tested and demonstrated to the engineering group at Trace Engineering's research and development laboratory. The bi-directional ability was demonstrated using manual control of the inverter's waveform in a process similar to method used by the existing SW series inverter. Since the intent of the modular inverter development is to utilize as much of the existing control software of the SW series inverter already developed, especially true of the utility interactive and battery charging software and since the initial hybrid inverter prototype did not include enough code space to include all of the SW series inverter's control software, only manually controlled utility interactive and battery charging ability was demonstrated at this point. This manual control was achieved by incorporating a potentiometer into the circuitry which varied the output voltage of the inverter, allowing the amplitude modulation system control used by the SW series to be simulated.

The final hybrid based modular inverter prototype was also demonstrated in the stand-alone mode at the annual review meeting at Trace Engineering's facilities in August of 1996 to the contract monitors - Holly Thomas (NREL), Ben Kropowski (NREL) and Ward Bower (SANDIA).

3.2 TASK 2 - PERFORMANCE OPTIMIZATION

3.2.1 Subtask 2.1 - Analysis of prototype's performance

Operation as a stand alone inverter was the initial development focus since stand alone operation presents some of the greatest technical challenges. Operation of inductive and capacitive loads was completed to help develop the protection and control systems. The prototype operated a wide variety of AC loads including resistive (heaters and light bulbs), motors (tools and an air compressor) and capacitive loads (power supplies and computers).

The output waveforms total harmonic distortion (THD) was monitored during the tests using a FLUKE 41B Power Meter system. The AC output voltage THD was found to range from 1% to 3 % for resistive loads and was less than 5% when operating inductive or capacitive loads.

The inverter was further developed to enable startup of a 3/4 horsepower air compressor by utilizing and advanced current limiting scheme which "soft started" the load by limiting the current being delivered to the motor. The high frequency switching pulse width modulation of the inverter system was controlled to allow limitation of the AC output current to a safe level. This level was varied by both the duration of the overcurrent condition and the temperature of the MOSFET transistors. A software based programmable system was developed to allow customization of the current limit system to different MOSFET transistors or to provide different control routines.

3.2.2 Subtask 2.2 - Identify and prioritize problem areas to be addressed

The area requiring the greatest engineering attention involved the idle power consumption of the hybrid modular inverter design when AC loads are small or when there are no AC loads. Minimizing the idle power consumption is critical for small standalone applications since it significantly influence the efficiency curve below 50 % of the inverter's rating.

Several circuit designs were tested to reduce the idle power consumption without adding excessive cost to the inverter. Methods such as co-inverters and multiple transformers were built and tested.

One method was found to be very successful - it reduced the idle power consumption of the hybrid modular inverter from approximately 30 watts to under 10 watts. This approach was simple and very low cost. It also can be easily eliminated either at the manufacturing or installation levels for applications which do not require low idle power consumption. This design change improves the flexibility of the modular inverter for use with a wider range of market segments and lower cost for use with a wider range of market segments with very little cost impact.

Another Important priority for the optimization of the hybrid modular inverter design was to improve the high power efficiency of the modular inverter. This optimization and development process in the Phase I effort was based solely on 12 VDC inverter since the low voltage inverters always have a lower efficiency due to the very high DC current that has to be processed. To further optimize inverter, higher DC voltage versions of the inverter design would need to be built and tested to determine the best ways to improve efficiency overall. Due to the limited development time, the higher DC input voltage versions was given a lower priority and the 12 volt DC version was the focus of this research and development.

The inverter protection and active current limiting system was also identified as needing further development and testing to ensure that the maximum reliability and performance was being achieved. The protection and active current limitation system were developed under Task 2.3 of the contract.

3.2.3 Subtask 2.3 - Develop a plan for addressing problem areas

A plan for the improvement of the idle power consumption was developed and then implemented. Many variants of the same idle reduction circuit design were tested in order to find the best method of reduce the power consumption. After approximately twenty different configurations were tested over a period of a few weeks, one method was found to reduce the idle power consumption from about 30 watts to about 12 watts. This level was the maximum amount we had hoped to achieve when we started (the SW series is considered very low with a idle draw of 16 watts for 4-kW of inverter).

Further testing and optimization of the method developed resulted in the reduction of the 12 watts of idle power consumption to under 8 watts with no additional hardware cost. This low consumption level was an unexpected result in this development and is even extremely low for commercially available non-sinewave inverters.

Further analysis of the inverter's design suggests that possibly another 2 watts may be eliminated by completing a minor redesign of the inverter's control board power supply circuitry.

The inverter protection and active current limit system were also further developed and refined. The motor starting ability was optimized during this development to allow the highest performance to be achieved without over stressing of the inverter. Further testing of the design at the production level will be required to ensure that manufacturing variability does not cause slight changes that would result in transistor damage or loss of inverter performance.

The same protection approach used in the 2-kW inverter module was also developed for the SW series and tested. This inverter has the additional complexity of having three power sections. The protection circuitry for the SW series was developed on a plug-in daughter card to allow calibration outside the inverter to guarantee the protection and performance levels. This circuit was tested and demonstrated to be of signifiçant value for that product. The further development of this circuit for the SW series was given to Greg Thomas to be completed outside the scope of this contract.

5.0 PROGRAM PLAN

This development program proceeded on schedule over the course of the first year. The change in the selected topology and the development of the commercially promising CO-sine inverter product did delay the schedule slightly.

Near the end of the Phase I program, Milt Rice, the primary design engineer, was killed in an airplane crash. This significantly delayed the completion of several of the final milestones as noted in the following sections.

5.1 SCHEDULE

With the loss of Milt the schedule was pushed back approximately 4 months while we regrouped and made the required personnel changes. Work on many of the Phase II tasks have been continued through Greg Thomas by using the existing SW series as a modular inverter. This allowed progress to be made on the modular inverter protection, control algorithms to allow paralleling on the modular inverters and the further optimization of the additional protection circuitry.

An engineering lab technician has been assigned the task of duplicating the existing hybrid modular inverter prototype and then completing preliminary tests on the two units to ensure that the performance can be duplicated and that the existing schematics and documentation are correct. One of the prototypes will than be sent to another Trace engineer, Mike Frost, for further testing, evaluation and development.

5.2 MILESTONES

PHASE I

M - 1.1.1 Complete definition of the topology for the 2-kW prototype inverter

This milestone was completed twice during the development process - once for the high frequency inverter design and once for the hybrid inverter design. The further development of the high frequency inverter into the CO-sine derivative product was completed outside of this contract.

M - 1.2.1 Complete design of the 2-kW prototype inverter

This milestone was reached in April of 1996 with the completion of the prototype breadboard construction of the hybrid inverter design. This prototype was then revised to allow incorporation of the components in the existing DR series inverter chassis.

M - 1.3.1 Complete 2-kW inverter prototype for performance testing

This milestone was reached in June of 1996 with the construction of the hybrid inverter design using the existing DR series inverter chassis.

M - 1.3.2 Complete successful operation of a prototype

This milestone was reached in June of 1996 with the successful operation of the hybrid inverter design.

M - 1.3.3 Complete initial testing of the 2 kW inverter

This milestone was reached in June of 1996 with the successful operation and the initial evaluation of the hybrid design. Additional testing was completed on various circuits intended to reduce the no load power consumption.

M - 1.3.4 Complete Task 1

This milestone to provide inverter topology design and verification of operation was reached in June of 1996. The result of this task was to design and prototype the construction of the 2-kW modular inverter for utility interactive and remote power applications.

M - 1.4.1 Complete Problem Identification and Development of Solutions

This milestone was reached in July of 1996 with the development of the low idle power consumption method and the advanced protection system for the inverters MOSFET transistors.

M - 1.4.2 Complete revision of the prototype

This milestone was reached in July of 1996 with the development of the low idle power consumption method and the advanced protection system.

M - 1.4.3 Complete performance verification of the revised prototype

This milestone was reached in August of 1996 with the further development of the low idle power consumption method and revisions to the transformer design to allow higher power and improved efficiency.

Demonstration of the prototype for utility connected and stand-alone applications as well as bi-directional ability was completed on a limited basis. The design was determined to be compatible with the control methods used to control the SW series inverter/charger for these application.

M - 1.4.4 Complete Task 2

This milestone to optimize the performance was reached in August of 1996 with the completion of the idle power consumption circuit development, prototype optimization, inverter protection circuit development, active current limiting system and additional testing.

6.0 DELIVERABLES

6.1 TECHNICAL REPORTS

D - 1.1 Report Summarizing Performance of Initial Prototype Inverter

A report summarizing the results of the testing was provided in February of 1997.

D - 1.1 Report Summarizing Performance of Revised Prototype Inverter

A report summarizing the results of the testing was provided in February of 1997.

6.2 PRESENTATIONS

A presentation was made at the NREL / Sandia Photovoltaic Program Review Meeting in November 1996 by Christopher Freitas.

THE POWER COMPANY
TRACE ENGINEERING
5916 - 195th N.E., Arlington, WA 98223 Phone (360) 435-8826 Fax (360) 435-2229

Initial Prototype Performance Summary

Summary Date: February 19, 1997

Summary Completed By: Christopher Freitas

Dates of Testing: June 1996 and July 1996

Testing Completed By: Milt Rice

Description of Initial Prototype: DC to AC power inverter for use as stand-alone AC voltage source. Inverter consists of a "H" transistor bridge utilizing paralleled MOSFETs operating a 20,000 hertz. The "H" bridge pulse width modulates the DC current into a transformer which both filters the DC pulse and steps the voltage up to the required AC output level. The design is able to operate in either direction - as an inverter or battery charger - although currently only the inverter mode has been developed and tested.

AC Output Waveform: Low distortion sine wave - 1 to 3% THD typical

DC Input Voltage - Nominal: The initial prototype is designed for 12VDC systems

DC Input Voltage Range: 11.0 to 16 VDC allowed, 11.5 to 15 VDC considered typical for specs/testing

AC Output Voltage - Nominal: 120 VAC / 60 Hertz

Continuous AC Output Capacity: 2.0 kW

Initial Prototype Performance Results

AC Output Voltage: 120 VAC RMS, 170 VDC Peak

AC Output Voltage THD: Less than 1% with no load, less than 3% full load (resistive)

AC Output Current THD: Less than 3% with a 2 kW resistive load and 12.0 VDC input

AC Output Voltage Regulation - No Load to Full Load: +2% and - 5%

AC Output Regulation - at 11.5 VDC: AC output voltage regulation +2% and - 5%

AC Output Frequency: 60 Hertz (no variation measured from no load to full load)

Continuous Capacity: Not measured - Unit was operated at 2 kW for 2 minutes

Maximum AC Output Capacity: Startup surge measured over 4.5 kW when starting AC incandescent light bulbs. Inverter momentarily current limited the AC output during startup

Idle Power Consumption - No Load, Full AC Output: 24 to 30 watts (varies with DC input voltage)

Efficiency: Not measured.

THE POWER COMPANY
TRACE ENGINEERING
5916 - 195th N.E., Arlington, WA 98223 Phone (360) 435-8826 Fax (360) 435-2229

Revised Prototype Performance Summary

Summary Date: February 19, 1997

Summary Completed By: Christopher Freitas

Dates of Testing: February 12, 1997

Testing Completed By: Christopher Freitas

Description of Initial Prototype: DC to AC power inverter for use as stand-alone AC voltage source. Inverter consists of a "H" transistor bridge utilizing paralleled MOSFETs operating a 20,000 hertz. The "H" bridge pulse width modulates the DC current into a transformer which both filters the DC pulse and steps the voltage up to the required AC output level. The design is able to operate in either direction - as an inverter or battery charger - although currently only the inverter mode has been developed and tested.

Design has been modified to include an additional inductor in series with the main transformer which reduces the idle power consumption when operating loads less than 100 watts. The inductor is switched out of the circuit when larger loads are operated. Design also has been revised by changing some of the characteristics of the main transformer to improve efficiency and continuous power capability.

AC Output Waveform: Low distortion sine wave - 1 to 3% THD typical

DC Input Voltage - Nominal: The initial prototype is designed for 12VDC systems

DC Input Voltage Range: 11.0 to 16 VDC allowed, 11.5 to 15 VDC considered typical for specs/testing

AC Output Voltage - Nominal: 120 VAC 60 Hertz

Continuous AC Output Capacity: 2.0 kW

Revised Prototype Performance Results

AC Output Voltage: 120 VAC RMS, 170 VDC Peak

AC Output Voltage THD: Less than 1% with no load, less than 3% full load (resistive)

AC Output Current THD: Less than 3% with a 2 kW resistive load and 12.0 VDC input

AC Output Voltage Regulation - No Load to Full Load: +1% and - 5%

AC Output Regulation - from 11.5 VDC to 15.0 VDC: AC output voltage regulation +2% and - 5%

AC Output Frequency: 60 Hertz (less than 0.1 Hz variation measured from no load to full load)

Continuous Capacity: Estimated at 2 kW - Unit was operated at over 2 kW for 10 minutes. The current heatsink for the transistors is not adequate to allow operation at the transistors and transformers abilities.

Maximum AC Output Capacity: Startup surge measured over 6.0 kW when starting AC incandescent light bulbs. Current limiting of the AC output was not detected at this power level. Inverter was able to start and run a 3/4 HP compressor with 50 PSI of air pressure but required limiting the AC output current during the start up (soft-starting).

Idle Power Consumption - No Load, Full AC Output: 6 to 8 watts (varies with DC input voltage) with the idle reduction circuit operating.

Efficiency: Estimated at over 80% at 50 watts, 83% at 2.0 kW with resistive loading. Peak efficiency estimated at approximately 90% for about 700 watts resistive.

Modular, Bi-directional Power Inverters for Photovoltaic Applications

Christopher Freitas

Trace Engineering Company, Inc.
5916 195th North East, Arlington WA 98223

Abstract. Description of the next generation of power inverters for both utility connected and off-grid photovoltiac applications. Includes explanation of the benefits gained by using modular constructed "building block" power sections for inverters up to 50 kVA of continuous power rating. Intended applications include both single and three phase power systems both with and without energy storage systems (batteries). Also includes a discussion of work being completed on using this modular inverter approach with a power inverter design currently in production under a Phase 4A1 PV-MaT contract.

WHY A "MODULAR" POWER INVERTER?

Trace Engineering is in the process of developing a "modular" power inverter for use in a wide range of power conversion applications. The inverter module will be able to be used alone or as a "building block" for the construction of larger power inverters. The use of this modular approach will provide the following benefits:

- **The modular power inverter approach reduces inverter cost**

  The basic power section components (transistor switches, transformer, control board and chassis) will be used for both small single inverter applications and larger, single and three phase applications. This allows the larger inverter applications to benefit from the substantially higher manufacturing volume of the smaller size inverters. Currently, for every 20 kVA or higher power inverter sold, thousands of smaller inverters (under 5 kVA) are sold. The present non-PV inverter market far exceeds the current and near term PV inverter markets. The modular approach allows PVs to benefit from these other markets.

- **The modular power inverter approach improves inverter reliability**

  The modular approach allows the mass production of a common "core" technology. This reduces the amount of "one off" designs required. The higher volume will allow greater use of statistical analysis methods and more expensive automated testing systems.

- **The modular power inverter approach improves system reliability**

  The use of inverter modules also allows the ability to incorporate N+1 redundancy into the design of a system (allows tolerance of one inverter module failure without loss of the system operation). The inverter modules will be "hot swappable" allowing servicing or upgrading to occur without shutting the system down. The use of a proven "building block" for new applications will result in improved product quality and faster time to market.

- **The modular power inverter approach improves inverter efficiency**

  The efficiency of the individual modular inverter power section will be similar to existing designs. For larger inverter systems, the modular power inverter approach will provide a substantial increase in the power conversion efficiency. This is achieved by only operating the number of inverter modules required by the load being powered. The additional inverter modules are turned on to keep each of the inverter modules at the highest efficiency point possible. When only a small load is being powered, the excess inverters modules will be turned off to eliminate their "tare" or "idle" power consumption. This ability is important for many non-utility connected, or off-grid, applications where the AC loads on the system vary substantially over the course of a day, or for applications where the AC loads cycle on and off frequently, such as with air conditioner or some water pumping applications.

- **The modular power inverter approach improves system efficiency**

  The use of inverter modules allows the installation of only as much inverter as is required for the application. Future growth can be accommodated, eliminating the need for installation of oversized power inverters. The modular design can also accommodate different inverter capacity per phase, allowing higher efficiency on systems where imbalanced distribution systems are encountered. If higher conversion efficiency is required, more inverter modules can be added to shift the point on the efficiency curve.

INVERTER VS. SYSTEM EFFICIENCY

The performance of a PV system using an inverter is not as simple as one might assume. The overall efficiency depends upon the inverter topology selected, the loads being powered and the usage patterns of the loads.

Inverter efficiency is a product of two inverter characteristics - the inverters "through-put" efficiency and its "idle / tare / no-load" power consumption. The through-put efficiency depends upon the inverters topology - such as the switching frequency and transformer design and operation. With many inverter designs, the idle power consumption dominates the losses at low power and the I^2R losses dominate at high power. Some high frequency inverters loose the majority of the power in the actual switching process. They often have their peak efficiency must closer to their full continuous power rating.

Trace Engineering currently offers a 4 kVA low frequency sinewave inverter design which features a low idle current draw (less than 16 watts with no load) that has a typical efficiency curve as shown in **FIGURE 1**. Many high frequency switching inverter designs often have a higher idle current draw and have a resulting efficiency curve as shown in **FIGURE 2**.

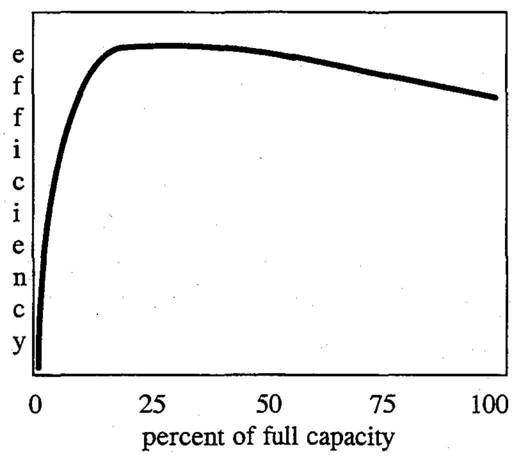


FIGURE 1. Low idle current design.

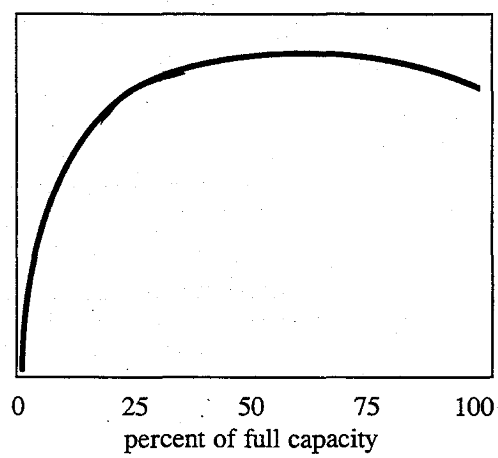


FIGURE 2. High idle current design.

Both of the inverters can be described as "high efficiency" and can even have the same peak and full load efficiency points. Depending upon the load level and load patterns, the system efficiency might be very different. If the loads are continuous and at a high power level, than the inverter shown in **FIGURE 2** would be acceptable. If the loads are comprised of a lower continuous base load and short periods of high loads, the inverter in **FIGURE 1** would result in a higher system efficiency.

FIGURE 1 is typical for a low frequency transformer based off-grid inverter. **FIGURE 2** is more typical of a utility connected high frequency switching type inverter.

MODULAR POWER INVERTER EFFICIENCY

The efficiency of a modular power inverter can be significantly better than either of the two previous examples. This improved efficiency is due to the operation of the modular inverter system and is not dependent upon achieving a higher efficiency for the inverter module itself. **FIGURE 3** shows the efficiency of a single inverter module. **FIGURE 4** shows the resulting efficiency of a modular inverter system made up of five of the same inverter modules.

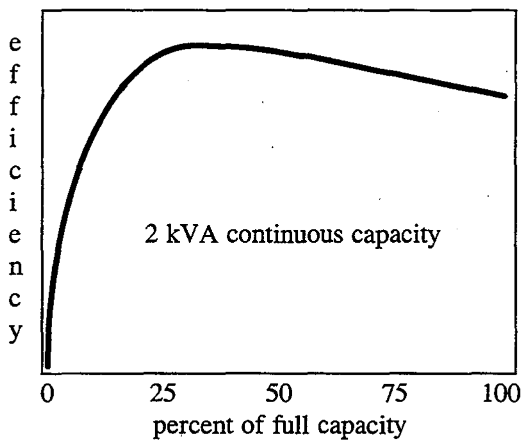


FIGURE 3. Single inverter module

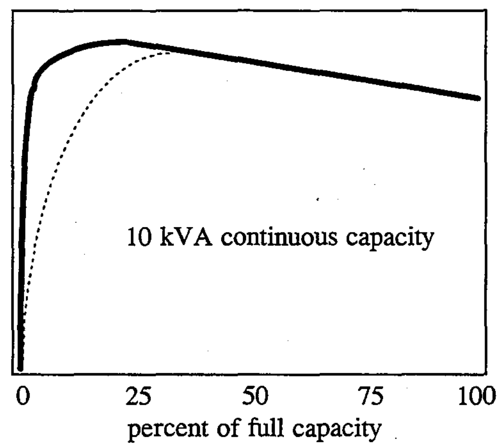


FIGURE 4. Modular inverter system.

The improved efficiency of the modular inverter system is achieved by turning off the unnecessary inverter modules when the inverter system is operating at low output level. The inverter modules are turned on as the loads increase one at a time in order to maximize the operating efficiency. The dashed line represents the resulting efficiency if all of the inverter modules were operated continuously.

If better efficiency is needed at high power levels, additional inverter modules can be added. More inverter modules will not reduce the low power efficiency since they are turned off at low power levels.

Note that the two efficiency curves have the same peak and full capacity efficiency.

UTILITY CONNECTED VS. OFF-GRID SYSTEMS

For utility connected systems the efficiency at high power levels is usually viewed as being more important than the efficiency at low power levels. This is often based on the primary value of the system being a "peaking" source during periods of heavy utility demand. This perspective is common with utilities.

If the system is privately owned and/or is "net" metered, then the overall energy production of the PV system may be viewed as being more important. This means that the efficiency over the course of the day at variable operating power levels will be the most important characteristic. Therefore, the efficiency at low and mid-point power levels must also be considered.

In off-grid applications the pattern of loads must be considered when evaluating the expected performance of a inverter system. For most residential and commercial PV applications, the inverter may operate at low power levels for extended periods of time. It is common to have the inverter only reach full power occasional. If the amount of time spent at high power levels is low, then the efficiency at full power is not as important.

In many off-grid applications, selecting an inverter size may be difficult due to lack of accurate information on the loads and usage. The modular inverter system allows expansion of the inverter system after installation. It also allows easier expansion of the system in the future as loads increase or finances permit.

The modular inverter system also allows installation of differing amounts of inverter per phase to better match the loads connected. This may allow reduced inverter cost in some cases. For example, it is not uncommon for a three phase system to have imbalanced loads on one of the phases. With a modular inverter system, one phase of a three phase system could be installed with the additional capacity. With standard inverter designs, all three phases would be increased. The larger inverter size would have higher idle power consumption and would operate significantly less efficiently.

INVERTER EFFICIENCY WITH INDUCTIVE LOADS

When an inverter is directly powering an inductive loads such as motors, the efficiency of the inverter is even more important. With an inductive load, the inverter has to process more power than the motor consumes, causing an additional reduction to the operating efficiency. When large inductive loads are to be powered for significant periods of time, a larger inverter should be considered. Using a larger inverter will improve the resulting system efficiency while operating the heavy load. If the larger inverter has substantially higher idle power consumption, then overall system efficiency would be significantly lower with the larger inverter.

The modular power inverter system allows "oversizing" of the inverter to allow efficient operation of inductive loads without the loss of overall system efficiency. No significant additional loss is incurred by having a larger inverter installed. It furthermore allows tuning of each system to achieve maximum efficiency for its particular loads, usage patterns and capacity requirements. This fine tuning of the system can occur after the original installation has been completed.

MODULAR VS. CO-INVERTER APPROACHES

One solution used in some of the high idle current inverter designs to remedy the poor low power level efficiency has been to include in the design a smaller "co" inverter. At low power levels the main inverter is turned off and the loads are connected to the smaller inverter. The size of this smaller inverter is from 1% to 10% of the main inverter continuous rating.

This approach does result in a significant improvement in the low power level efficiency. Often, the efficiency peaks and then drops off and then peaks again at the main inverters optimum efficiency. Depending upon the capacity of the co-inverter, the drop when switched to the main inverter may or may not be significant. FIGURE 5 shows a typical efficiency curve for a co-inverter equipped unit.

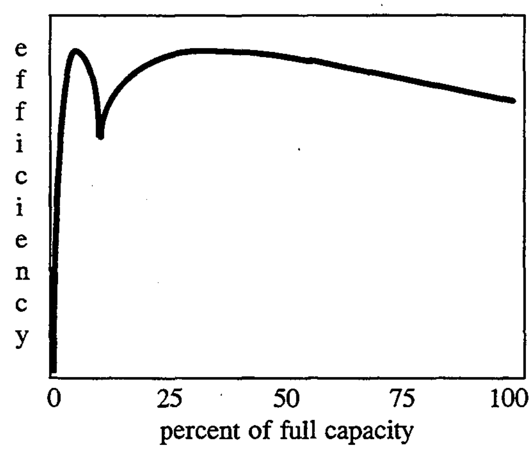


FIGURE 5. Co-inverter system.

Co-inverters add complexity to the design of the inverter. It can be difficult to design the inverter to allow the co-inverter to be offered as an option. This approach does not provide the flexibility benefits provided by the modular inverter approach. It is useful on smaller, single inverter applications where the modular inverter system can not be utilized.

The co-inverter also adds significant cost. The cost reduction benefits of the modular inverter's common power section design and components is not realized with this approach. The importance of efficiency at low power levels is almost unique to inverters used in PV applications.

Co-inverters also do not allow hot swapping of inverter modules or provided redundancy in the event of a single unit failure.

DEVELOPMENT OF A MODULAR INVERTER SYSTEM

Trace Engineering has been actively developing this modular inverter concept for the last two years. This research and development program has been partially supported by a PV-MaT Phase 4A1 contract. This support has been very important and has enable much faster progress to occur compared to developing the system with our own resources.

This work has been divided into two separate efforts - one team working on the development of a 2 kVA power inverter module, and a second team working on the interface and overall control of the multiple inverter modules. The second team has been developing the modular approach using a current generation inverter to use as the inverter module. This will allow implementation of the modular inverter system sooner

ACKNOWLEDGMENTS

Give credit to Milt Rice, Steve Johnston and Greg Thomas.
Thank NREL and Sandia National Labs for support

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1997	Phase I - Annual Technical Progress Report, August 1995 - August 1996

4. TITLE AND SUBTITLE
Development of a Modular, Bi-Directional Power Inverter for Photovoltaic Applications; Annual Technical Progress Report, August 1995 - August 1996

5. FUNDING NUMBERS
C: ZAF-4-14271-08
TA: PV705101

6. AUTHOR(S)
C. Freitas

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Trace Engineering Company, Inc.
5916 195th N.E.
Arlington, WA 98223

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
SR-520-23401

11. SUPPLEMENTARY NOTES
NREL Technical Monitor: H. Thomas

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE
UC-1280

13. ABSTRACT *(Maximum 200 words)*
During the first year (Phase I) of this research and development effort, Trace Engineering Company completed the following work: conducted a review of possible inverter designs and identified preferable approaches; developed and built initial "breadboard" prototypes of two different inverter designs; evaluated the performance through computer modeling and laboratory testing; selected one of the two designs for further development into a manufacturable prototype; refined the design to reduce no-load power consumption (reduced the consumption from 30 watts to less that 10 watts for a 2-kW power inverter module); developed an advanced hardware-based protection system for the MOSFET transistors; built a manufacturing prototype of the selected design using production methods and materials (the prototype was built up in an existing product chassis to emphasize the compatibility of the design with current production methods and components); demonstrated the final Phase I prototype at the annual review meeting held at Trace Engineering in August 1996; and submitted the final Phase I prototype to Sandia National Laboratories for additional testing.

14. SUBJECT TERMS
photovoltaics ; modular inverters ; Photovoltaic Manufacturing Technology ; PVMaT ;

15. NUMBER OF PAGES
30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102