

PHOTOVOLTAIC POWER CONDITIONERS: DEVELOPMENT, EVOLUTION, AND THE NEXT GENERATION

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ABSTRACT

Market-place acceptance of utility-connected photovoltaic (PV) power generation systems and their accelerated installation into residential and commercial applications are heavily dependent upon the ability of their power conditioning subsystems (PCS) to meet high reliability, low cost, and high performance goals. Many PCS development efforts have taken place over the last 15 years, and those efforts have resulted in substantial PCS hardware improvements. These improvements, however, have generally fallen short of meeting many reliability, cost and performance goals. Continuously evolving semiconductor technology developments, coupled with expanded market opportunities for power processing, offer a significant promise of improving PCS reliability, cost and performance, as they are integrated into future PCS designs,

This paper revisits past and present development efforts in PCS design, identifies the evolutionary improvements and describes the new opportunities for PCS designs. The new opportunities are arising from the increased availability and capability of semiconductor switching components, smart power devices, and power integrated circuits (PICs).

INTRODUCTION

The conversion of free and abundantly available solar energy into cost competitive electrical power has been the goal of many PV related efforts for over 15 years. In the post-Tesla culture, ac electricity is, by far, the most common form of electrical power used in the U.S.A. and the world. Utilities have adopted ac as a standard of generation and transmission. Hence, for PV to become a significant power supplier, the dc from the PV must be converted to utility compatible ac power by a PCS. The PCS must conform to all of the rigorous requirements that are necessary for operation with the utility,

This puts the PCS at the center of a challenge. That challenge calls for high reliability and performance of the PCS today, with a continuous examination of evolving, germane technologies that have relevance and adaptation potential for improvement of the PCS,

Both stand-alone and utility-interactive PV power systems have been designed and are widely operational in the U.S.A. and elsewhere throughout the world. Some of the important cost effective niches for PV power applications have been identified as small stand-alone systems for remote area power requirements for lighting, communications and basic electrical needs.

Limited numbers of utility-connected PV systems have been installed in the past, but most of these systems have

been installed as demonstration systems. Several utility-connected systems have recently been installed because "value added" features such as line-voltage regulation, demand-side-management or the elimination of the need to replace conductors or a transformer have resulted in a cost effective utility-interactive application (1).

A block diagram of a utility-interactive PV power system is shown in Figure 1. The system consists of a PV array subsystem, a PCS, a utility-interconnection subsystem, and a control subsystem. The PCS is a dc-ac power inverter that includes the system operation functions, the dc- and ac-side controls, and the protection functions. Each of the subsystems function collectively to meet all of the external and internal requirements imposed on the system. External requirements include the utility systems' power quality requirements, operational voltage windows, connection constraints, safety and protection. Internal requirements include characteristics of the PV array, such as voltage and current interdependence, maximum power point tracking, waveform generation, internal timing functions, start-up and shut-down functions. The dynamic interplay between the external requirements and internal requirements put the PCS in a critical path. It must be reliable, efficient and cost effective.

The dominant cost driver of a PV system is the PV array with its costs ranging from \$4.00 to \$8.00 per peak watt. The PV costs depend upon the quantity purchased, the module technology, and the efficiency requirements. The PCS cost is in the range of \$.50 to \$1.50 per maximum rated watt output. The other balance-of-system (BOS) costs include structures, wiring, disconnects and

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protection. Their collective costs range from \$1.00 to \$4.00 per watt, again depending upon system size, voltage ratings, structure requirements, and system design. With the PCS in a critical path that directly impacts the size of the array, BOS costs, and the delivered cost of power, it is obvious that improvements in PCS performance can have a positive leveraging effect on total system size and cost,

This paper focuses on the utility-interactive PCS for PV applications. It summarizes development and evolution of PCS designs, and gives insights into the opportunities for design and development of the next generation of PCS hardware for PV applications,

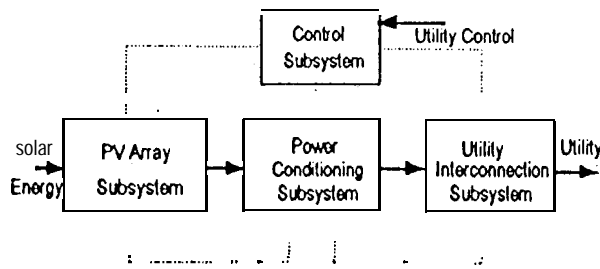


Figure 1. Block Diagram of a Utility-Interactive PV Power System

EVOLUTIONARY DEVELOPMENT OF THE PCS

A multi-pronged approach was taken by the U.S. Department of Energy (DOE) to accommodate three potential market sectors for PV applications. PCS hardware was developed for PV applications for single-phase and three-phase utility connections, PCS units for residential PV systems in the output range of 1-10 kW, intermediate PV systems in the 15-300 kW range, and central station PV in the 0.3 - 5 MW range were investigated (2,3,4,5,6,7,8). Utility-interactive PCS hardware designs were also evaluated with regard to their performance and cost in PV applications,

The initial cost and efficiency goals set forth in the DOE 5-year PV R&D plan, for PCS hardware, are shown in Table 1. The goals and the values typically attained by installed hardware are given for comparison. Table 1 clearly shows that existing PCS technology did not meet the U.S. DOE cost and performance goals.

There have been many new advances in semiconductor technologies such as PIC and smart power components that are applicable in PCS hardware. These components will improve performance and reduce costs of the PCS, but further studies to determine the technical and economic viability of PCS designs that could incorporate these new, high performance semiconductor devices are required. The smart power concept refers to the integration of power switches, control functions, protection and sensing functions into one package,

Size In kW	Efficiency Goal	Efficiency Attained	Cost Goal \$/W	Cost Attained \$/W
1-10	95%	85-93%	\$.30	\$.85-1.50
15-300	96%	92-95%	\$.12	\$.75-1.25
300- 5000	98%	93-97%	\$.08	\$.65-1.00

Table 1. Commercially Available PCS Goals and Attained Costs and Performances.

Close cooperation among users and developers of both new semiconductor technologies and PCS hardware for all applications has been initiated. The DOE/PV division, "Sandia National Laboratories (SNL), Jet Propulsion Laboratory (JPL), the Electric Power Research Institute (EPRI), the private sector of industry, universities, and utilities have begun to work together in program planning, advanced design conceptualization, hardware fabrication, and evaluation of new PCS designs that will enable PV systems to be more competitive with conventional electrical generation methods. Two workshops have been held. These workshops have been instrumental in bringing important and active players together. A continuation of the government-industry partnership in R&D of PV systems and applications, to keep the U.S.A. competitive in world markets, is planned.

The development and the evolution of PCS hardware follows as a discussion of the three size categories. The discussion is categorized into residential-, intermediate-, and central station- sizes. Further discussion and applications analysis brings the reader up to date with suggestions for incorporating new semiconductor technologies into the PCS design.

Residential PCS Systems "

Various PCS topologies for residential applications are available today, and there likely will be new topologies, such as resonant inverters, emerging in future designs. Only one inverter configuration is given here as an example, but other topologies are discussed in many publications (4,5). Figure 2 shows a transistorized, single-bridge inverter used in an early PCS design,

Single-phase, residential-size (1-10 kW) PCS units developed in the 1976 to 1984 time frame used hundreds of discrete components in their circuits for control and drive functions. They used power transistors and silicon controlled rectifiers (SCRs) for the power switching elements. Some designs were modifications of frequency converters, uninterruptible power supplies, or adjustable speed drives for ac motors. A few models were designed specifically for PV applications. The designs included line-commutated and self-commutated inverters. Algorithms and controls included maximum power point trackers,

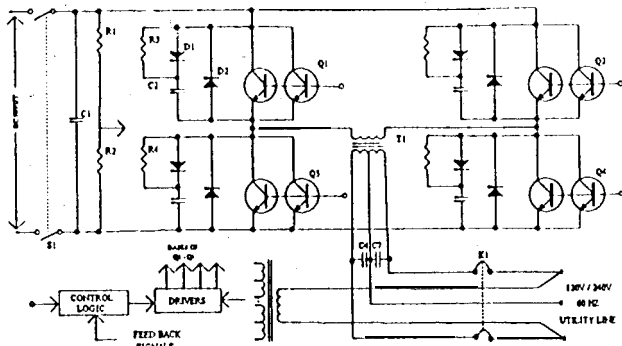


Figure 2. Single-Phase Transistor Bridge Inverter

over- and under-voltage trips, over- and under-frequency trips, wake up and shut down functions, and methods to detect and prevent "islanding". "Islanding" may occur when the utility grid is disconnected from local 'island' loads that remain energized by PV systems that do not detect the island and do not disconnect from the load.

The wave shaping methodologies used to create the sinusoidal output of the PCS included stored pulse pattern, pulse-width-modulation (PWM), and 'bang-bang' or hysteresis type controls using stored or reference wave forms. Voltage-sourced and current-sourced designs were used. PCS designs with and without transformers were developed, as were uni-polar and bi-polar (center-tapped) dc input circuit configurations,

Today's single-phase PCS technology has evolved from using hundreds of discrete components to designs using fewer discrete components controlled by microprocessors or application specific integrated circuits (ASICs). The designs have generally converged on a PWM waveform synthesis with current-sourced control methodologies. Power switches used today include insulated-gate-bipolar-transistors (IGBT) and power metal-oxide-semiconductor field-effect-transistors (MOSFET). Transformer isolation, when used, is high-frequency-link or line-frequency types. Operating performance and costs attained are shown in Table 1,

Residential-size PCS technology has continued to advance in recent years due, in part, to DOE PV program support. Other efforts from EPRI, universities, private industry, and other government agency support has also added to the advancement. In addition, other sectors of the electronics industry have developed and evolved components, such as ASICs, PICs, and new integrated circuits (ICs) that have been used in and improved PCS design further,

Substantial operating experience of residential-size PCS hardware in PV applications has been acquired, and the issues associated with today's PCS cost, performance, safety, and utility integration have been identified. The

original cost and performance goals still have not been met. Issues such as hardware certification, needed for meeting safety codes, have arisen, and are currently being addressed with the PCS manufacturers.

intermediate-Size PCS Systems

Development of medium-size (20 kW-200 kW) PCSS is important because they are a convenient size to be used independently or as building blocks for larger systems. A single PCS, or multiple PCS's of this size operating in parallel, can provide power at commercial complexes or industrial plants.

Early three-phase intermediate-size (20-200 kW) PCSS available in the United States reflected designs that were developed 10 or more years earlier for industrial applications, such as motor speed controls and uninterruptible power supplies. These designs were highly material-intensive rather than process-intensive. Process intensive generally refers to the use of semiconductors to replace heavy magnetic and capacitor functions. There were basically two types of intermediate-size PCSS that were commercially marketed for PV applications. The first type was primarily a modified, uninterruptible power supply. It was a self-commutated PCS that provided high quality power. The second type was a line-commutated PCS. The line-commutated PCS required substantial filtering to provide the equivalent harmonic and VAR performance of self-commutated systems. The early designs used SCRs, large or parallel transistors, and gate-turn-off (GTO) devices for power switches.

There were approximately twenty-five different design concepts in the intermediate-size PCS development program. Some were only conceptual designs, but a few were pursued to hardware phases, and purchased for use in individual PV system experiments. There was a major difference from the residential PCS program where some units were developed, from concept to working prototype, exclusively for PV. Most available intermediate-size hardware evolved from other power electronic applications. Consequently they generally did not meet price and performance goals for PV applications,

Design studies were funded during the mid 1980s to identify new and innovative approaches for PCS hardware. U.S.A. manufacturers' such as GE, Westinghouse, UTC, Garrett, Helionetics, Gould, Firing Circuits, Omnion, UPG, and Abacus participated. Three universities and one laboratory (Caltech, Cal Poly at San Luis Obispo, MIT and JPL) also participated. Many promising designs were evaluated, but few were ever built. The key result of the design studies was that eight different designs were found capable of meeting or exceeding the cost and performance goals of \$.20/watt and 96% efficiency. Both cost and efficiency were estimated with respect to site-specific utility electrical service. Only four of the above manufacturers remain to supply intermediate-size hardware for PV applications today.

Today's three-phase intermediate-size PCS technology has evolved from using mostly discrete components to using a blend of discrete circuits controlled by microprocessors and ASICs. The designs have generally converged on a PWM waveform synthesis with various feedback methods, and current-sourced control methodologies. Both transformer isolation and transformerless designs are used. Operating efficiencies of today's intermediate size PCS hardware range from 89% to 96% depending upon operating voltages of the

sector have not been fully met. Continuing efforts, over a period of about two decades, brought the performance of central station PCS designs closer to the goal as compared with the other two sectors. As a result, the central station PV power source is closer to utility interactive acceptance today.. Continuing PCS development is still needed.

The DOE efforts in central station PV PCS development, as of late, have been practically eliminated because the

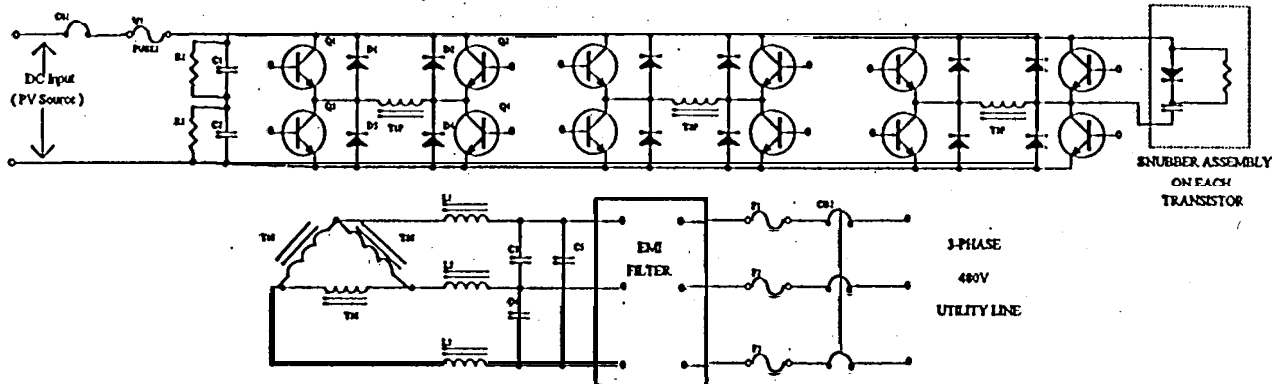


Figure 3. PWM, 6-Pulse Transistorized Bridge

application and power levels. The power switches used are generally IGBTs. Single unit costs of today's intermediate-size PCSS range from \$0.65 to \$1.20 per peak watt depending upon manufacturer, maximum power rating, and options.

The circuit of Figure 3 is presented as an example of an intermediate-size PCS design. This topology shows a pulse-width-modulated, six-pulse inverter using transistor switches. The transistor-based systems offered improved power quality and control compared with their SCR counterparts, but costs were higher.

Central Station PCS Systems

Meeting DOE goals of cost and performance for central station-size systems required novel and innovative designs that incorporated the new and advanced power semiconductors. Cost and efficiency were projected for GE, Westinghouse and United Technologies Corporation PCS designs (2,8). The cost and efficiency of prototypes and production hardware of large, state-of-the-art PCSS were projected (8). Figure 4 shows a twelve-pulse, self-commutated, 500-kW thyristor inverter topology, as an example. Two of these Helionetics units were placed in operation at the Lugo installation in Hesperia (2,8). The Sacramento Municipal Utility District (SMUD) installed two PV systems using a 1-MW, line-commutated PCS designed by Omnion Power Engineering, and a 1-MW, self-commutated GTO PCS designed by Toshiba (8).

Again, the DOE performance and cost goals for this

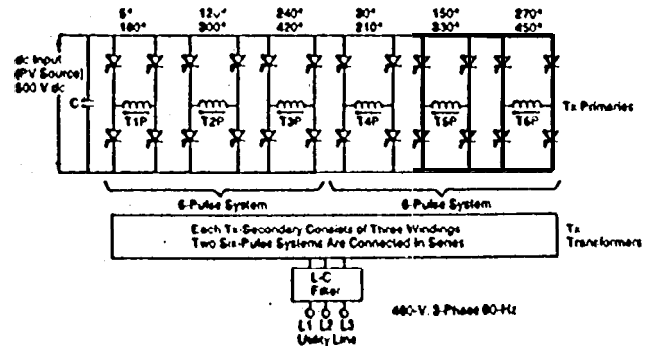


Figure 4. Twelve-Pulse, 500-kW, 3-phase inverter.

generated power costs for the PV system are not competitive with conventional power generation costs today,

CURRENT STATUS AND ACTIVITIES

PV power applications are currently concentrated in small stand-alone PV systems or intermediate- and residential-size utility-interactive systems. Consequently, the development of low cost, highly efficient and reliable PCSs in the small to medium power range is a focal point for assuring the viability of PV systems as an alternative energy source. Current efforts in utility-interactive BOS dwell on development of residential- and intermediate-size PCS hardware.

PCS technology is the key link in a utility-interactive PV system and because of its critical role, it is often

described as the weak link. Some designs still use hundreds of discrete parts with virtually no mass production, quality control, or industry standardization. Some new electronic component technologies have advanced to the point where they could improve efficiency and reliability of PCSs. These new technologies include PICs, smart power, ASICs, novel integrated circuit (IC) architecture, and improved packaging techniques. Some new semiconductor devices have matured to the point of being available off-the-shelf, however, only a few components are currently available for PCS applications,

Smart power development in the U.S.A. and in other countries, today, are diverse and target the lucrative automotive and motor control industries. Many of the smart power devices being developed for these industries could be applied to PCSs. The full impact of using this promising technology on PCS systems is not fully known at this time, but assessment of the impacts of using smart power in the PCS for the PV system are planned by DOE, SNL and JPL.

A source of present-day DOE funding opportunities include the Small Business Innovative Research (SBIR) program, Modular power processing hardware for PV applications is an objective of this effort. There is a need for modular and manufacturable PCS hardware that is a multipurpose electronic converter with code-certifiable solid state ac and dc interfaces and control circuits. Larger modular sizes (50-250 kW) are needed for PV operation in conjunction with batteries, diesel generators, and fuel cells for applications such as rural stand-alone plants and village power applications. The use of state-of-the-art technology such as ASICs, PLAs, and microprocessors is encouraged to promote modular designs that can use advanced automated manufacturing processes,

Smaller (50-250W) PV module PCSS that operate as an integral part of available PV modules and provide an output of 110 V at 60 Hz of utility quality power are currently being developed. Commercialization of this development could revolutionize the PV industry by providing an 'ac PV module' that has built-in maximum power point tracking and ac safety interface functions. It could essentially be an ac appliance that supplies power, and would avoid the do-side issues of array mismatching, array utilization, and shadowing. Utility-side connections would still have to meet applicable codes but the interface would be easier with proven devices.

As part of the National Photovoltaic Program's Balance-of-System Initiative, DOE, through SNL's PV Systems Applications Department is funding an effort to determine the status of smart power and PIC technologies. This effort is intended to provide literature research and a tabulation of available new smart power components and PIC technologies that are applicable to PV systems and the associated PCSs.

A smart power workshop was an important part of this effort, It provided an opportunity for the component manufacturers and the BOS manufacturers to interact

with each other, and to learn about the needs, capabilities and limitations of each discipline. It also provided a forum for dissemination of information and comparison of notes in the development of the emerging smart power technology. Preliminary feedback indicated that PCS manufacturers were interested in incorporating this new PIC technology into their products. Applications in the automotive industry and ac motor control could become near-term, significant markets for smart power, and the resulting mass produced, low cost components could be adapted to PV applications.

The first workshop on smart power was held at the California institute of Technology (Caltech) on May 20, 1987 (9). Many presentations were made to cover both technology and applications. The workshop concluded that no real technical barrier existed that would prevent the application of smart power concepts to PV-specific systems, in addition, solutions to current reliability problems that constrain PV systems operations today may be evolved by using smart power.

Much development had occurred in PIC and smart power devices and their applications since the first workshop. Therefore, a second workshop was held on December 8-9, 1993, at Caltech (10). Sponsors included (DOE-PV), (SNL), National Renewable Energy Laboratory (NREL), Interagency Advanced Power Group (IAPG), (EPRI), Power Electronics Applications Center (PEAC), and (JPL). High caliber smart power manufacturers not only participated in this highly advertised, high quality workshop, but demonstrated their enthusiasm and commitment to PV PCS developments as well.

The results of this workshop were fourfold. First, the workshop provided an understanding of the current state-of-the-art of smart power and PIC technology. Second, the strengths and technological barriers of PIC technology were identified. Third, usage of PIC technology in various PV applications was identified. Fourth, programmatic steps to further the uses of the smart power technology were identified. These are: (1) develop a plan to transfer smart power/PIC technology from smart power industry to PV PCS industry. (2) develop R & D program to identify smart power/PIC devices for integration into PV PCS units, (3) establish and maintain a current database on smart power/PIC hardware, (4) plan and organize a workshop on smart power in 1995 and (5) monitor the development of a small 115V AC (50W or less) modular inverter adaptable to PV modules, under SBIR and other programs.

The papers and presentations identified smart power circuit topologies and their impact on performance and cost in terrestrial, space and defense systems. A PIC and smart power market was scoped out, and technological barriers and challenges were analyzed. Papers that discussed the dynamics of the evolution of the PCS design in PV systems were presented (11), it was generally agreed that, while many issues that were identified in the first workshop remained unchanged, resolution of some important issues, such as better voltage isolation, was encouraging.

NEXT GENERATION DEVELOPMENTS

The new revolution in smart power or PICS offers renewed opportunities for increased reliability and efficiency, and reduced cost of PCSs. The ASIC is also one of the latest innovations in electronic power control technology. Further applications of these new technologies in PV PCS controls will advance the controllability, with improvements in speed of response, accuracy, reliability and fault monitoring, while at the same time realizing a long-term reduction in cost. Steps involved in the implementation of smart power technology include: selection of switching devices, analog and digital signal processing, signal isolation, current and temperature sensing, and obtaining chip size magnetics and capacitances. Monolithic IC circuitry incorporating power switches and hybrid packaging would improve the ruggedness of PCS hardware in the future.

A PCS effort that is tailor-made for smart power technology is one using an integrated, nearly monolithic, PCS to further the concept of an "ac PV module". The ac PV module idea is being supported by funding from the Environmental Protection Agency (EPA), SBIR, and SNL. The ac PV module concept was discussed within the DOE PV program as early as 1975, but the necessary electronics was not of-age at that time. An "ac PV module" would facilitate expansion of installed PV systems and add new dimensions. The idea here is to use a hybridized PCS integrated with smart power module on the panel itself for AC or DC output.

A combination of high voltage and high frequency operation in smart power designs permits the use of digital control such as PWM, resulting in high efficiency designs. Efficiencies of up to 95 percent and substantial reductions in volume and weight are obtainable. Smart power implementation could enhance the reliability of a PCS because of dramatic reduction in the number of discrete parts. Reduced number of interconnections also enhances the reliability. Smaller size, no external parts, higher operating frequency, better feedback and lower production cost, enhances smart power and PIC implementation in PCS designs.

Technology Barriers

Isolation between high-voltage devices and low-voltage circuits is a limitation within PIC and smart power devices today. A concerted and dedicated developmental effort is expected to resolve the barrier in the near future. Development of devices and associated fabrication processes that produce high-voltage, high-current PICs at reasonable cost will be essential to accelerate the widespread use of the technology,

In order to achieve higher efficiency for high-voltage, high-current devices, the on-state losses and switching losses will have to be reduced. Improved device designs and fabrication processes to yield lower on-resistance and reduce chip size are needed.

The cost of implementing smart power technology, at its current cost, in small quantities, is significantly higher than using readily available discrete components. The initial benefit is in system reliability. The cost of smart power will go down with higher volume production, in synergism with automotive and motor drive applications. Ultimately, everyone will benefit through economies of scale.

CONCLUSIONS

The evolution of PCS hardware for PV systems (residential-, intermediate-, and central station- sizes) was reviewed. The residential- and intermediate- size PCS hardware has evolved from modified industrial process hardware, such as uninterruptible power supplies and motor drives to mostly well designed electronic PCSs. These PCSs use microprocessors, ASICs, PLAs and specialized ICs for their controls and drive circuits. The residential- and intermediate-size PCS design has converged to PWM topologies using either power MOSFETs or IGBTs as power switches.

The central station PCS is typically a custom design for a specific application today, and generally could easily incorporate new control devices. Central station size PCS hardware will generally use either SCRS or GTOS for their switches.

Many developments and new applications in PICS and smart power devices have taken place since the first smart power workshop in 1987. The second workshop provided additional impetus in addressing remaining difficulties and to steering this technology towards expanded use in various power systems with low, medium and high voltage and current ratings. A government-industry-university partnership is also functioning to achieve this goal. Periodic information exchanges through future workshops and publications will be helpful in extending and utilizing the merits of PICs.

A low-power PV system can use a highly integrated PCS such as in an AC PV module. The applications of smart power technology in such PCS hardware could provide more cost effective, utility-interactive PV systems and help expand the PV utility-interactive market, world-wide.

Presently, smart power technology finds applications in computers, electrical appliances, instrumentation, brushless DC motors, stepper motors, automatic test equipment, avionics, printers, security systems, automobiles and telecommunications. Terrestrial, space, military and aircraft power systems are finding increasing use of this technology as it matures and its voltage and current ratings increase. This expanding market could quickly include PV systems, battery chargers, AC motor drives, and PCSs.

Using smart power technology results in dramatic reduction in the number of discrete parts and interconnections. Consequently, the reliability increases.

The cost of smart power devices will go down with higher volume production in synergism with above mentioned applications. Thus, economy of scale will benefit PV systems and other applications. As a result, the merits associated with smart power/PIC technology qualify it as the future research and development component of the balance-of-system Program of DOE,

In order to utilize the full potential of smart power technology, present technological barriers will have to be reduced, Potential users in all sectors should be educated and assisted by the PICs industry through application support, Areas benefiting more from smart power applications need to be better identified. Frequent discussions of issues, in common forums, will be organized. Periodic workshops on smart power technology are planned,

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