POWER CONDITIONING SUBSYSTEMS FOR PHOTOVOLTAIC CENTRAL-STATION POWER PLANTS:
STATE-OF-THE-ART AND ADVANCED TECHNOLOGY

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ABSTRACT

Through the combined efforts of governmental agencies and laboratories, private organizations, universities and electric utilities, substantial progress has been made in bringing photovoltaic (PV) systems closer to commercial feasibility.

The future availability of central station power conditioner subsystems (CS-PCS) that are efficient, safe, reliable, and economical will play a key role in the acceptance of large-scale PV energy by electric utilities. To accelerate the development of such CS-PCS hardware, the Department of Energy's Photovoltaic Division, as part of its Five Year Plan, has established a goal of a reliable, 98 percent-efficient CS-PCS that in volume production will cost \$0.07/W_p. This will help make PV power economically competitive with electric power derived from conventional energy sources. Various governmental agencies and private organizations are cooperating to try to achieve this proposed goal.

The combination of a dwindling federal budget for PV research and development (R&D), and the reluctance of American industry to accept the high economic risks involved in its own PV R&D efforts, could shift the leading edge of PV-PCS technology development to foreign competition, in general, and to Japanese industry, in particular.

INTRODUCTION

This paper is an overview of the technical and near-term cost requirements that must be met to develop economically viable power conditioning subsystems (PCS) for large-scale, central, PV power stations. The paper also surveys various already commercially available PCS-hardware suitable for use in today's central PV power stations.

To accelerate the development of efficient, safe, reliable, and economical central-station power conditioning subsystems (CS-PCS), the U.S. Department of Energy (DOE), through the Five Year Plan of its PV Division, has established a goal (Table 1) of a reliable, 98 per-

cent-efficient CS-PCS that in volume production would cost \$0.07/W_p (1). The realization of this goal would help make PV power economically competitive with electric power generated from conventional energy sources.

PCS Size	Cost, \$/Peak W	Efficiency %	Energy Cost \$/kWhr*
Central Station	0.07	98	0.108
Intermediate	0.16	96	0.117

*Energy costs are based upon applications in the southwestern region of the United States and upon the following far-term considerations: modules, PCS and system costs, and 2-axis tracking systems, and 30-year life expectancy.

Table 1. U.S. Department of Energy Photovoltaic Division 5-Year Plan Cost and Efficiency Goals

Examination of the cost and efficiency parameters associated with state-of-the-art PCS technologies, reveals that the PCSs now available fall short of the DOE goals. To meet these goals will require novel and innovative designs that incorporate the new and advanced power semiconductors now becoming available. Thus, this paper also reviews federal/industry activities in research and development (R&D) of advanced PCSs that will contribute to the attainment of fully competitive, large-scale PV power stations (Table 2).

Performance Requirements for Central Station Power Conditioning Subsystems

A central PV generating plant, like its residential counterpart, is an example of a utility-interactive, dispersed-generation system (2). Thus, to understand the design requirements of a CS-PCS, it is essential to review the technical requirements of a utility-interactive PV system and its subsystems.

A utility-interactive PV system (Figure 1) consists of a variety of subsystems: a PV array subsystem, a power conditioning subsystem, a utility interconnection subsystem, and a control subsystem (3). The PV array subsystem converts solar energy into direct current (dc) electrical power and delivers it to the PCS through the dc interface. The array subsystem also provides protection and necessary

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Manufacturer	dc/dc Converter	dc/ac Inverter	Method of Power Control	Ancillary Commutation Components
State-of-the-Art Configurations:				
Windworks	N/A (not applicable)	12-Pulse Line-Commutated SCR Inverter	Line-Commutated Phase-Angle Control	N/A, due to line commutation
Helionetics	N/A	12-Pulse Self-Commutated SCR Inverter	Phase-Shift Modulation	Required
Toshiba	GTO Thyristor	12-Pulse Self-Commutated GTO Converter	dc/dc Converter for Power Control	N/A, due to GTO usage
DOE/SNL Studies of Central Station - Power Conditioning Subsystem Configurations:				
United Technologies Corporation	N/A	12-Pulse Self-Commutated Inverter (Either GTO's or SCR's Implementation)	PWM (Pulse-width modulation)	N/A for GTO Designs Required for SCR Designs
General Electric	N/A	12-Pulse Self-Commutated GTO Inverter	PWM (Pulse-width modulation)	N/A, due to GTO usage
Westinghouse	GTO Thyristor	12-Pulse SCR Inverter	dc/dc Converter for Power Control	N/A, due to line commutation

Table 2. Comparison of Central-Station Power Conditioning Subsystem Configurations (5,6,7,8)

Figure 1. Block Diagram of a Utility-Interactive Photovoltaic System

electrical isolation between the PCS and the array, and may include experimental instrumentation for monitoring the performance of the array. The utility interconnection subsystem, through the alternating current (ac) interface with the PCS, provides for synchronization with the utility and, if necessary, acts to electrically isolate the PV system from the utility. The control subsystem, operating through the PCS, oversees the performance of the entire PV system. It also enables overall coordination of the protection of the system, communicates status information to the utility dispatch center, and, if desired, provides an information and tracking feedback loop with the PV array. In central PV stations, the PCS may also process operational commands from the utility dispatch center.

In operation, the PCS converts dc power from the array into ac power, provides for an optimum amount of power to be extracted from the PV array for any given insolation and environmental conditions, matches frequency and phase of the voltage desired by the utility, and provides protection not only for its internal components but also for the equipment external to the PCS (3,4).

To achieve a compatible integration of the PV system with the utility, it is essential that the design of the PCS accommodate the dynamic range of interactions between the PV system and the utility grid. These arise from changes in both grid conditions and the output of the PV array. The proper and safe interconnections of PV subsystems require not only an identification of their mutual functional constraints, but also a knowledge of how to select or design the PV subsystems within such constraints. These constraints, therefore, are important in the selection or evaluation of a PCS that is suitable for central station PV systems.

Energy considerations will vary in different parts of the U.S. The data used in this paper refers to the Southwest region of the U.S. and may differ in other regions.

COST AND EFFICIENCY REQUIREMENTS

Along with taking into account the compatibility of the PCS with the utility, it is necessary to consider the contribution of the PCS to the cost of PV-generated electricity. The leveled busbar cost of the energy that the PV plant produces is a figure of merit that best characterizes the performance of a PV system. Obviously, since the PCS is an integral component of the overall PV system, its cost and performance will affect the price of unit energy.

Cost and Efficiency of Central Station Designs

There are several approaches to CS-PCS designs that are described in the following sections. The cost and energy efficiency data for proposed and state-of-the-art designs are shown in Tables 3, 4, and 5.

Intermediate Power Conditioning Subsystems.

A CS-PV system may include a large PCS or multiple intermediate-type PCSs. The cost and efficiency of both of these types of PCSs are reviewed in this section.

Through contracts awarded by the Sandia National Laboratory (SNL), innovative approaches to the intermediate power conditioning subsystems were studied in 1981 (9,10). Based on results of these studies, Table 3 shows the cost and efficiency projections for both 100 and 1000 units of these PCSs, when considered on the basis of 1981 dollars. An annual production of 100 PCSs, each capable of handling 50 kW, will be required for a 5-MW plant. Estimated prices are obtained from Figure 2, in which relative price is plotted against annual production quantity. The projected costs for 100 50-kW PCSs do not include the additional costs of external weather-proofing, enclosures, transformation, and protection of the utility interface. On that basis, the projected prices for these proposed designs appear to be very competitive in the near term to the large, prototype, state-of-the-art PCSs now available.

Manufacturer	PCS Power Rating, kW	Efficiency, %	100 Units Cost, \$/W	1000 Units Cost, \$/W
General Electric	92.0	95.3	0.146	0.117
Westinghouse	90.0	94.2	0.188	0.15
	150.0	94.8	0.136	0.109
United Technologies Corporation	80.0	95.4	0.136	0.109

Table 3. Cost and Efficiency Projections for Proposed PCS Designs

It is clear from Table 3 that the projected efficiencies, of the intermediate PCSs are less than the proposed DOE goal of 96 percent.

Figure 2. Relative FOB Cost of Intermediate Power Conditioning Subsystem versus Annual Quantity

Large Power Conditioning Subsystems

The cost and efficiency of both prototypes and production hardware of large, state-of-the-art PCSs are depicted in Table 4. The efficiency figures represent estimated rather than measured values. Although several of these presently available large PCSs have efficiencies that approach that of the DOE goal,

Research Organization	Status	PCS Size ^b	Maximum Power Energy Efficiency, % (Estimated)
Windworks	Production Hardware	1000 kW	97.5
	Production Hardware	300 kW	
Helionetics	Production Hardware	75 kW	93.0
	Production Hardware	750 kW	96.0
Toshiba	Prototype Production	750 kW	97.0
	Prototype Production	1000 kW	97.0

^aEnergy cost varies from \$0.14 to \$0.15/kWhr. Calculations are based upon applications in the southwestern region of the United States, present PCS costs, and the far-term costs of modules and systems.

^bApproximate cost of CS PCS is between \$0.45 to \$0.55/W_p.

Table 4. Industry Central-Station Hardware Status^a

they neither satisfy the cost goal (Table 1) nor the energy cost projections. Thus, while the energy cost of these systems is \$0.15/kWhr, the proposed DOE goal is \$0.108/kWhr.

Table 5 shows the cost, efficiency, and energy costs of several conceptual designs of PCSs for central stations. These conceptual designs meet neither cost and efficiency goals nor the projections of energy costs. The energy cost of these conceptual designs, based on a life expectancy of 30 years, more closely reflects the energy cost in the DOE projections rather than the energy cost for both large-and intermediate-sized, state-of-the-art PCSs. Thus, while the energy cost of these conceptual systems is \$0.114/kWhr, the DOE proposed goal is \$0.108/kWhr.

Manufacturer	PCS Power Rating, MW	Projected Efficiency, %	Projected Costs, \$/W (b)	Energy Cost, \$/kWhr (c)
General Electric	5	96.7	0.105	0.112
Westinghouse	5	96.8	0.134	0.114
United Technology	1	96.7	0.13 ^(a)	0.114
^(a) Each 50 units/year, ^(b) PCS cost, ^(c) Entire PV plant				

Table 5. Projected Results of DOE-Funded Central-Station Power Conditioning Subsystem Studies

Although there are discrepancies between the DOE proposed goals for cost and efficiency and the values derived from the conceptual designs, the latter approximate the DOE-proposed energy-cost goals. Thus, further research and development of new hardware are needed to determine whether the cost and efficiency goals can be met.

Table 6 provides a calculated relationship between efficiency and cost for CS-PCSs. This analysis is based upon the configuration of future PV systems.

Efficiency (%)	Relative Change in Cost of PCS Compared to Its Cost at 98% Efficiency
99	\$13/kW Lower
98	0
97	\$13/kW Higher

Table 6. Relative Change in Cost with Change in Efficiency

LARGE, STATE-OF-THE-ART POWER CONDITIONERS: TECHNICAL CHARACTERISTICS

This section deals with a comparative analysis of three, presently available, large power conditioners suitable for use in central-station PV applications. A technical summary is provided in Table 2.

1. 500-kW and 750-kW self-commutated Thyristor Inverter (Manufactured by the DECC Division of Helionetics Corporation).

Two 500-kW, self-commutated inverters have been operating in a 1-MW PV installation at the ARCO Solar Lugo Installation in Hesperia, California. Multiple 750-kW units have been installed and are operational at the ARCO Solar Carrisa Plains Installation, California (Figure 3). The installed capacity is 6 MW. Except for being packaged in a self-contained, outdoor enclosure, the 750-kW units are electrically similar to the 500-kW units. Harmonic reduction is accomplished by waveform synthesis.

Figure 3. 12-Pulse, Self-Commutated, 750-kW Inverter Assembly (Courtesy of DECC Division of Helionetics)

2. One-Megawatt, Line-Commutated Inverter (Manufactured by Windworks, Inc.).

At present, as part of the Sacramento Municipal Utility District (SMUD) Phase I program, a 1-MW, line-commutated inverter is operational for PV central-station application at a SMUD installation. Harmonic reduction is accomplished with filters. Figure 4 shows various views of this inverter's subassemblies.

3. One-Megawatt, Self-Commutated Inverter (Manufactured by Toshiba, Inc.).

At present, a 750-kW inverter is installed at the ARCO Solar PV installation at Carrisa Plains, California. A 1-MW unit also will be supplied to SMUD for its Phase II central-station installation. Filtering of the harmonics produced is accomplished by

Figure 4. 1-MW, Photovoltaic Inverter Manufactured by Windworks, Inc. (Courtesy of Windworks)

waveform synthesis and an output filter. Figure 5 shows an inverter assembly similar to the 1-MW inverter assembly.

Figure 5. 1-MW, Photovoltaic Inverter Manufactured by Toshiba, Inc. (Courtesy of 3T Tanakaya, Inc.)

NEW DESIGN OPPORTUNITIES

The widespread use of central-station PV plants will occur only if they are competitive with other sources of electrical energy in terms of busbar energy and reliability. Yet, until recently, the concepts for grid-interactive, central-station PV systems and their optimized PCSs were only in the exploratory planning stage. In contrast, small-size (up to 10 kW), second-generation, process-intensive, cost-effective, and efficient power conditioners for residential systems already were commercially available. Similar, but larger power conditioning subsystems have become available only recently.

In addition, the previous lack of appropriate power semiconductor devices led to material-intensive designs burdened with components that assist in semiconductor switching (commutation) or with cumbersome techniques to accomplish harmonic filtration. Designs of uninterruptible power supplies (UPS) and adjustable dc-speed drives have become the standard

of the PV-PCS-related industry. Because of production volume and lack of foreign competition in this sector, there was little need for innovative designs with their attendant reductions in cost. This situation now is changing as both new and advanced semiconductor devices and more advanced PCS designs are emerging from foreign industrial competition.

To date, most of the larger, multi-kilowatt, government-funded, PV-demonstration projects use inverters that were retrofitted for PV applications from the designs of UPS. The cost for power conditioning from these UPS designs varied between \$0.50 to 1.10/W_p, depending on their size. Since the cost goal for a CS-PCS (Table 1) is \$0.07/W_p, the cost range of these UPS-derived power conditioners was unacceptable for future PV systems. Obviously, significant technical innovations were needed to improve large, PV-specific PCSs.

Meanwhile, recent commercial incentives (substantial tax credits, third-party financing, etc.) opened new opportunities for the development of multi-megawatt, central-station PV system power plants. This, in turn, necessitated re-evaluation of the designs for large PCSs for PV applications. The large-scale ARCO PV installations at Lugo and Carrisa Plains in California are recent PV success stories. In addition, the joint SMUD-DOE venture shows promise on the even larger scale of 100 MW.

A much needed technical innovation in PCSs recently has come in the form of developments of commercial, large (100-MW), gate turn-off (GTO) thyristors and other fast-switching power devices. These developments have opened the door to new approaches to cost-effective, large PCSs for PV applications. Most importantly, these multi-megawatt PC units offer promise of meeting the DOE's projected cost and performance goals.

In the United States, at present, there are no commercially available intermediate- or large-scale inverters that use gate turn-off (GTO) thyristors for application in UPS, PV and other dispersed storage-and-generation systems.

GTO thyristors, representing advanced devices, are commercially available in Japan. The Japanese are producing large, multi-megawatt power conditioners using GTOs. Since GTOs presently are not being produced by American manufacturers, the United States has fallen behind Japan in the manufacture and application of GTOs and other power semiconductor devices. American semiconductor manufacturers and equipment designers, however, now are showing increasing interest in GTO devices.

Based on initial and optimistic test results with these newly developed technologies, the DOE-funded program has embarked on a course of research and development aimed towards building a testable prototype of a multi-megawatt type inverter. It is to be specifically designed to meet both the technical needs and the cost objectives of a grid-interactive PV central station.

THE DOE CENTRAL-STATION PCS PROGRAM

Various central-station PV system and PCS hardware study programs have been initiated by industry, the U.S. government, DOE, and the Electric Power Research Institute (EPRI). A major thrust of these programs is to identify optimal, conceptual, central-station PCS topologies that could provide improvements in energy cost as compared to present, state-of-the-art PCSs for given power, voltage and performance levels.

In 1983, a government-industry workshop dealing with large, multi-megawatt PCS technology for PV applications was initiated by DOE and hosted at EPRI. This workshop brought together the two major areas of PV systems expertise: PV cell/module technology and PCS photovoltaic balance-of-systems. The objective of the workshop was to determine the optimal voltage and megawatt size of future photovoltaic central-station PCSs. Previous assessments had indicated an optimal configuration of 5 MW at 2000 Vdc. A 5-MW, 800-Vdc (center tap ground) arrangement was agreed upon because of the present unavailability of photovoltaic modules that are able to withstand a higher voltage stress and still retain a projected lifetime of 20 to 30 years.

Under an SNL/DOE multi-year plan, PCS configurations have been solicited from industry for future hardware implementation. The plan stresses the use of innovative and process-intensive concepts that make use of advanced electronic components. To take future cost-effective designs into account, the plan also emphasizes flexibility for upward voltage-scaling to accommodate high-voltage PV modules of the future. Concurrently, the need for an innovative design of a PCS for multi-megawatt PV systems was identified. Contracts were signed with both industry and universities to fill this void. The 5-MW block concept will be developed as far as the budget will permit, possibly beyond the proof-of-concept stage and to the point of a scaled-down prototype.

U.S. industry, seemingly lagging in this area, will be encouraged to stay active and competitive with foreign developments in the power electronics marketplace. This will require component development incentives to encourage better PCS hardware designs.

Recent Program Results

Large, multi-megawatt, second-generation power conditioners, with potentially high efficiency and lower cost, have been studied for PV applications by Westinghouse, General Electric, and United Technologies. The results of these studies are summarized in Table 2 and Table 5. It should be noted that the three design approaches suggest the use of GTO semiconductor devices in the PCS design.

While pursuing the long-range objective of designing large, multi-megawatt PCSs, efforts also are being made to be responsive to present, central-station economic perspectives. The intermediate PCSs will be re-evaluated as a possible option now for central-station applications. Within this research-oriented activity, U.S. industry will continue to work with smaller, high-tech designs until the concept of the large, multi-megawatt PCS can be fully accepted economically by both the utilities and industry.

CONCLUSIONS AND WHAT NEEDS TO BE DONE

A cost-effective PCS, with a track record of trouble-free operation, will increase utility interest in the use of PV systems. It also will improve the prospects of sales of PV systems in both national and international markets. To achieve the DOE's proposed cost and efficiency goals for PCSs requires additional research and development efforts. Efficiencies of several state-of-the-art CS-PCSs already have come close to the desired efficiency goals. However, energy costs are substantially greater than the proposed DOE goal and milestone. Thus, it is likely that properly implemented second-generation designs can meet both cost and efficiency goals.

The viability of central-station PCSs, with respect to multiple units (greater than 500-kW) in parallel, has been proven with presently available designs. Multiple-kilowatt, power conditioner subsystems are operational at the ARCO installations at Lugo and Carrisa Plains, as well as the SMUD installation. Their operational track record is good. Knowledge gained at these installations will be beneficial in the design and operation of large, multi-megawatt, central-station PCS units.

New power semiconductors, such as GTO thyristors, offer the prospects of substantial PCS cost reduction and improved delivered energy costs. Their use should be considered in future CS-PCS designs. Pulse-width modulation technology for large-scale PCSs has not been

implemented as yet and should be examined for CS-PCS applications. In such configurations, keeping the need for filtering of the PCS's output to a minimum will provide trouble-free utility integration. With such PCSs, the system loop stability will be at a maximum while risks of system resonances will be at a minimum. Improving filtering techniques and elimination of commutation components will result in increased efficiency and reliability.

Further research is required to determine the technical and economic viability of multiple, intermediate-size inverters for central-station PV systems.

Cooperative efforts among DOE-Photovoltaic Division, DOE-Electric Energy Systems Division, EPRI, SNL, JPL, universities, utilities, IEEE, and the private sector in program planning, conceptualizing advanced designs, hardware fabrication, test evaluation, and formulation of standard guidelines, have achieved substantial progress in bringing PV systems closer to commercialization. Continued efforts by all participants will enable photovoltaic systems to be competitive with conventional sources of energy and, therefore, be widely used. The government-industry partnership in the research and development of PV systems must continue.

To date, American industry stresses high economic risks as detrimental to their own pursuit of research and development efforts. At the same time, the federal R&D budget has been dwindling. These two conditions could lead to a shift of the leading edge of technology development in photovoltaics to foreign competition. This, in turn, could lead to a significant setback to the PV segment of U.S. industry. Continuation of this shift will allow the Japanese industry to become undisputed leaders in this technology and would, for years to come, preclude American industry from cornering its share of the market.

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