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EXECUTIVE SUMMARY

WORKSHOP ON POWER CONDITIONING

FOR

ALTERNATIVE ENERGY TECHNOLOGIES

Denver, Colo., May 9-11, 1979

By

D. R. SMITH
SANDIA LABORATORIES

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WORKSHOP ON POWER CONDITIONING FOR ALTERNATIVE ENERGY TECHNOLOGIES

EXECUTIVE SUMMARY

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Sandia Laboratories

As various alternative energy technologies such as photovoltaics, wind, fuel cells, and batteries are emerging as potential sources of energy for the future, the need for development of suitable power conditioning systems to interface these sources to their respective loads becomes more apparent. Since most of these sources produce DC electricity while most electrical loads require AC, an important component of the required power conditioning units is a DC-AC inverter. Although each of these units will interface with an AC load and perhaps the utility grid, the respective source characteristics will be greatly different. This Workshop on Power Conditioning for Alternative Energy Technologies was particularly appropriate at this time as a first step in coordinating the development of power conditioners for each alternative energy technology to avoid duplication of effort and to provide an opportunity to discuss problems in power conditioning development which may be common to several technologies.

The Workshop was sponsored by the U. S. Department of Energy and was co-hosted by the Solar Energy Research Institute and Sandia Laboratories. It was held in Denver, Colorado, at the Hilton Hotel, May 9-11, 1979. Its purpose was to bring together the expertise of those working various alternative energy R and D areas, power conditioning manufacturers, component suppliers, program administrators, and potential users. Discussion topics included assessments of current technology, identification of operational requirements with a comparison of requirements for each source technology, the identification of future technology trends, the determination of mass production and marketing requirements, and recommendation for program direction.

During the first day, invited papers of a tutorial nature (abstracts and vugraphs of which appear in these proceedings) were presented. Concurrent working group sessions were held on the

second day, three in the morning and three in the afternoon. The morning groups were divided according to source technology: photo-voltaics, fuel cells and batteries, and wind; while the afternoon sessions were structured according to system size and application: large grid-connected systems, small grid-connected systems, and stand alone and dc applications. A combined session was held on the third day with summaries presented by the working group leaders. Written summaries of these sessions are also included in these proceedings.

Highlights of the working group sessions are presented in this Executive Summary. For more detailed discussions, the reader is referred to the individual working group summaries.

Power conditioning technology development has taken place in the past, primarily in four main application areas: uninterruptable power supplies (ups), AC motor speed control, high voltage DC (HVDC) transmission, and VAR generation for harmonic filtering and power factor correction. More recently, efforts have been undertaken to develop power conditioners for battery and fuel cell load-leveling applications (BEST and Con Ed programs) and for photo-voltaic sources. As a result, hardware has become available, either off-the-shelf or as a developmental unit, in power ratings from less than 1kW up to 14MW. Efficiencies of greater than 90% are currently achievable, and with advanced technology, efficiencies of 96% full load and 92% quarter load appear feasible. Although projected costs in quantity production differ, especially at the lower power ratings, it appears that achievable cost goals are: less than \$200/kW for 10kW residential units and about \$50/kW for 14MW units. Both line commutated and force commutated designs exist at both ends of the power range, and neither appears more viable than the other at this time.

Power quality is an important issue for utility-connected systems and will become more important as large numbers of systems are connected to the grid. A need was expressed by several of the grou

for power quality standards. Although there is no utility consensus on the matter, power factors in the range 0.9 lead/lag and harmonic distortions of 10% for current and 5% for voltage are being considered.

Reliability figures have been established by experience with UPS systems. Design life of 10-20 years appears acceptable, and 17,000 hour MTBF, corresponding to 5-7 years for photovoltaic systems, are achievable. There is a need for more units to be built and fielded to obtain better reliability data. One year warranties will probably become standard, and repair by local technicians appears feasible for residential systems.

Safety is also an area of concern, especially for utility-connected systems in which the possibility of energizing a "dead" utility line exists. Utility management of system controls appears to be necessary in order to protect utility personnel while servicing transmission and distribution equipment, unless an automatic, fail safe disconnect scheme can be developed.

In addition to uniform power quality standards, and a fail safe disconnect method, a computer simulation study was recommended in order to assess the impact of a large number of dispersed power systems upon the utility grid, looking at network resonances, stability, and EMI effects. The results of the study could be examined experimentally at a later date when actual systems are connected to the grid. The feasibility of producing power conditioners at even lower costs than currently projected should be investigated, and a limited number of "high risk" advanced technology power conditioning development programs should be funded. Designs which minimize raw material and utilize available low cost solid state power devices are preferable. The development of low cost magnetics and dc switchgear should be pursued. For dc systems and possibly even for large photovoltaic ac systems, there is a need to develop a line of low cost dc-dc converters.

Thus, even though inverter technology is relatively mature, there are many problems which still need to be solved in the development of power conditioners for the alternative energy technologies. Also, as new power electronic devices, such as power FET's and gate-turn-off SCR's, become available in power ranges of interest and at low cost, power conditioner designs offering greater reliability and even lower cost become a real possibility.

SUPPLEMENT TO:

POWER CONDITIONING FOR PHOTOVOLTAICS

By

D. R. SMITH
SANDIA LABORATORIES

*Use \$1.70/lb to determine cabling cost

POWER CONDITIONING IN OTHER PV APPLICATIONS EXPERIMENTS

APPLICATION	OPERATED BY	PCU MFR.	KVA RATING
IRRIGATION PUMPING MEAD, NEBRASKA	MIT-LINCOLN	NOVA	22.5 (3x7.5)
PARK HEADQUARTERS NAT, BRIDGES, UTAH	MIT-LINCOLN	CYBEREX NOVA	50 5 (UPS)
RADIO STATION BRYAN, OHIO	MIT-LINCOLN	NOVA	5
TEST FACILITY LEXINGTON, MASS.	MIT-LINCOLN	ABACUS	6
TEST FACILITY ARLINGTON, TEXAS	UT-ARLINGTON MIT-LINCOLN	WINDWORKS	8
RADAR FACILITY MT. LAGUNA, CALIF.	DOD - MIRADCOM	DELTA	60
MISSISSIPPI COUNTY COMMUNITY COLLEGE BLYTHEVILLE, ARK.		DELTA	300
NW MISSISSIPPI JUNIOR COLLEGE SENATOBIA, MISS.		TBD (RFQ)	3x50 1x2
DC APPLICATION SCHSHULI VILLAGE ARIZONA	NASA-LEWIS		3.5kW
REMOTE VILLAGE UPPER VOLTA, AFRICA	NASA-LEWIS		1.8kW
VILLAGE POWER SYSTEM SAUDI ARABIA	SERI	TBD (RFQ)	350

DEPARTMENT OF ENERGY PERSPECTIVES
ON
POWER CONDITIONING DEVELOPMENT

BY

A. S. CLORFEIN
DOE/ET

U.S. DEPARTMENT OF ENERGY PHOTOVOLTAICS PROGRAM

OVERALL OBJECTIVE:

To achieve major cost reduction—leading to competitive life-cycle costs—by aggressively pursuing advanced research, technology development, and real-world testing, to support the large-scale transfer of the technology to the market place.

<u>BASIC GOALS</u>	<u>MODULE PRICES (FOB)*</u>	<u>SYSTEM PRICES*</u>	<u>PRIME APPLICATION</u>
1982	\$2.80/peak Watt	\$6-13/W	Remote/International
1986	\$0.70/peak Watt	\$1.60-2.20/W	Residences
1990-2000	\$0.15-0.50/peak Watt	\$1.10-1.30/W	Utilities

*1980 constant \$

Figure 1

PHOTOVOLTAIC PROGRAM STRATEGY KEY ELEMENTS

- **Substantial Price Reductions via:**
 - **Aggressive R&D to establish technical feasibility of advanced materials and devices (CdS, alpha-Si, semicrystalline Si and other thin-film devices, photochemical and thermophotovoltaic systems, etc.)**
 - **Intensive technology development of flat-plate and concentrator systems (both Si and GaAs)**
 - **Engineering analyses and technology development to lower the balance-of-system costs (e.g., power conditioning, storage, structures and support, marketing and distribution, etc.)**
- **Design, development and testing of complete PV systems in actual users' environment**
- **Emphasis on grid-connected distributed residences as an early U.S. wide-scale application**
- **Support PV performance criteria and test standards development**

Figure 2

KEY MILESTONES IN THE PHOTOVOLTAIC RD&D PROCESS

MILESTONE	DEFINITION/REQUIREMENT
Technical Feasibility (TF) of Components	Technical feasibility is reached for a particular technology when: (a) stable and reproducible performance characteristics have been achieved; (b) a laboratory-scale process has been defined that yields products with consistent characteristics; and (c) analysis indicates that mass production is technically feasible and likely to yield a technically and economically viable product after suitable technology development.
Technology Readiness (TR) of Components	Technology readiness is achieved: (a) with a successful subscale demonstration of all of the individual steps in a production process that would yield economically competitive and reliable products if produced in sufficient quantity, and (b) when prototypes are available for intensive performance and reliability analysis.
System Feasibility (SF)	System feasibility is achieved in a given application when a photovoltaic system concept is first carried through design, installation and operation in an actual user's application.
System Readiness (SR)	System readiness is accomplished when fully integrated systems, using available technology-ready components or prototypes thereof, are designed, built and successfully operated in an actual user's environment.
Commercial Readiness (CR) of Components and Systems	Commercial readiness in a given application class is accomplished when products or systems are offered for sale at a given price.

Figure 3

COLLECTOR AND BALANCE-OF-SYSTEM COMPONENTS

**RESEARCH, DEVELOPMENT AND DEMONSTRATION
PROCESS FOR COMPONENTS AND SYSTEMS**

Figure 4

Storage Battery Program

Performance Goals Are Different for Different Missions

Parameter	Requirement		
	Photovoltaic System Storage	Utility Load Leveling	Electric Vehicle
Cost (to O.E.M.)	\$30-35/kWh	\$30/kWh	\$35-40 kWh
Cycle Life	3000 Cycles	2000 Cycles	800-1000 Cycles
Service Life	7-10 Years	10 Years	3-10 Years
Energy Efficiency	70-80%	70%	50%
Energy Density	Not Applicable	Not Applicable	140 Wh/kg
Power Density:			
Peak (15s)	Not Applicable	Not Applicable	200 W/kg
Sustained	Not Applicable	Not Applicable	70 W/kg
Typical Installation Size	5 kWh - 600 MWh	200 MWh	30-50 kWh
Duty Cycle	3-14 h Discharge 6-10 h Charge	4-10 h Discharge 4-7 h Charge	2-4 h Discharge 1-6 h Charge
Environmental Impact	NIL	NIL	NIL

Storage Battery Program Funding History

Storage Battery Program

Expected Battery Requirements for Various Applications to Photovoltaic Systems

CHARACTERISTIC

APPLICATION

Remote
Site

Single
Residence

Multiple
Residence

Commercial/
Industrial

Central
Station

SYSTEM

Storage Capacity (kWh)	0.05-1000	5-30	10-2000	150-10	10^5 - 6×10^5
Power (kW)	0.001-2	2-10	5-500	50-5000	5×10^4 - 10^6
DC Voltage	2-400	50-350	50-600	50-600	750-2500

BATTERY/CELL

Cost (\$/kWh)	25-100	<40	<40	<40	<35
Maximum Rate	<C/50	C/3-C/5	C/5-C/7	C/5-C/14	C/2-C/6

Duty Cycle

Float, May be
1-Year Cycle

Daily Cycle,
Rapid
Changes

Daily Cycle, Less
Rapid Rate Changes

Daily Cycle,
Possible Daily
Discharge

Life

4-10 Yrs.

2000-3000 Cycles, 7-10 Yrs.

SA-028-8/78

78-10211M/2-11

U.S. NATIONAL PHOTOVOLTAIC CONVERSION PROGRAM BUDGET

	FY 1979 (Estimated Millions of Dollars)	FY 1980 (Requested Millions of Dollars)
<u>Advanced Research and Development</u>		
Advanced Materials/Cell Research	31.5	29.0
High Risk R&D	2.5	13.0
Research Support and Fundamental Studies	<u>5.0</u>	<u>5.0</u>
Subtotal	39.0	47.0
<u>Technology Development</u>		
Low-Cost Solar Arrays	30.0	33.0
Concentrators	8.0	10.0
Balance-of-Systems	<u>0.0</u>	<u>13.0</u>
Subtotal	38.0	56.0
<u>Systems Engineering and Standards</u>		
Systems Definition	3.9	2.0
Systems Development	7.4	10.5
Performance Criteria and Test Standards	<u>2.0</u>	<u>2.0</u>
Subtotal	13.3	14.5
<u>Tests and Applications</u>	13.2	12.5
<u>Federal Photovoltaic Utilization Program (FPUP)</u>	<u>15.0</u>	<u>0.0</u>
Total	<u><u>118.5</u></u>	<u><u>130.0</u></u>

Figure 8

PHOTOVOLTAICS PROGRAM ORGANIZATION

Figure 10

POWER CONDITIONING EQUIPMENT FOR THE
INTEGRATION OF NEW ENERGY SOURCES

BY

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DOE/ELECTRICAL ENERGY SYSTEMS

Power Conditioning Equipment for the Integration of New Energy Sources

Dietrich J. Roesler

Electric Energy Systems Division

Background

Present nationwide electric systems are designed around electric power generation stations. With the emergence of dispersed electric energy generation through new source technologies such as solar photovoltaic, wind, fuel cells and battery storage devices, the present concept of power delivery must undergo radical design changes to meet the required safety and reliability standards. This was recognized by DOE and late in 1978 the Electric Energy Systems (EES) Division was given the explicit mission to develop and carry out a program to integrate new source technologies into the electric power system by utilizing power conditioning equipment. The EES division is well qualified to perform this integration task because of its involvement in near-term and longer range development in electric energy system technologies. Current EES programs include Load Management activities and efforts that are aimed to develop more efficient Systems and to improve system reliability. As part of this effort, EES is participating in the development of power conditioning equipment for the BEST facility and the 4.8 MW Fuel Cell Demonstration Project. To manage these efforts efficiently, EES has established working relationships with other DOE Organizations, ETS divisions, the Utility and EPRI.

Discussion

The EES division is part of the Office of Solar, Geothermal, Electric and Storage Systems (ETS). The purpose of EES's involvement in the integration of new energy sources with the utility grid is to:

- Define and substantiate current and future efforts for power conditioning integration projects.
- Facilitate coordination within DOE, with EPRI and utilities and with other federal departments.
- Provide guidance for scheduling of projects and estimated funding.

To initiate actions, EES will prepare a development plan for power conditioning integration projects. It is anticipated that the recommendations of this workshop will become an important part of this plan.

The objective of the plan is to coordinate the power conditioning effort between the involved activities in order to develop reliable,

efficient, low cost power conditioning equipment within the required time.

Figure 1 represents a potential electrical energy system for the future, combining traditional electric power generators with new electric energy sources. The operations of a complex network such as that requires new operating concepts and the development of power conditioning equipment. In addition, a number of problems and issues, such as --generation impact, ownership, operational control, equivalent firm capacity, cost/price for backup power, value/price for excess energy, storage, harmonics, VAR control etc. -- have to be resolved before the integration of a substantial number of new energy sources into the utility grid can be attempted.

Figure 2 shows a block diagram of a system powered by a new energy source. The system consists of the new energy source, the power conditioning unit and the interface with the utility grid. As can be seen, the power conditioning unit includes all the equipment necessary to connect a new energy source to the utility grid.

Figure 3 shows the principal groups presently involved with the development and integration of PC equipment.

The EES Division in response to its mission will be the focal point of this program. In this role, EES will coordinate the efforts between the principal groups, will manage programs funded by EES and/or other source technology divisions, will distribute findings resulting from the projects and will initiate new and modify existing programs as felt necessary to accomplish the objectives.

The implementation of this plan will provide a mechanism for the timely integration of new source technologies into the power grid, and the organizational set up, will ensure minimal overlapping of programs.

Figure 4 gives the basic concepts which will be followed to develop reliable, efficient, low cost power conditioner systems.

The PC equipment will be developed in three distinct groups; the "Studies and Simulation", the "Design and Hardware Verification" and the "Pilot Production for Commercial Readiness." Before a project is transferred from one group into the other, a set of individual milestones has to be met.

The development of the PC equipment starting from studies and ending up in pilot production is straightforward. Major emphasis has to be placed on the generation of practical requirements and

standards. The requirements and standards have to be strict enough to produce safe and reliable equipment, but loose enough to produce equipment with a low cost.

The evaluation of each individual project will be based on the two major objectives; high efficiency and low production cost. If the efficiency and/or cost goals are not within the established limits, the particular project will be re-directed or cancelled. Table 1 shows efficiency and no load loss goals of power conditioners for near term and long term efforts.

Table 1 Efficiency and No Load Losses

	Near Term			Long Term		
Categories	1	2	3	1	2	3
Rated Load (%)	91	93	96	93	95	97
Half Load (%)	88	90	94	90	92	95
No Load Losses % of Rated Power	<5	<4	<2	<3	<2	<1

Category 1: Residential
Category 2: Load Centers
Category 3: Central Power

Figure 5 represents the cost projection of PC systems for different New Source Technologies, such as Photovoltaic and Wind, Fuel Cells and Batteries. The projected cost for the PC production unit is on the average about 1/5 to 1/6 of the current cost.

Up to date, a number of studies and simulations have been performed, hardware has been designed and built and a number of projects have been successfully completed. Based on these efforts, there should be no doubt that with proper planning and funding the goals which have been set for the Integration of New Energy Sources with Power Conditioning equipment can be met.

FIGURE 1

Integration of New Source Technologies

PC: POWER CONDITIONER

FIGURE 2

SYSTEM SCHEMATIC

FIGURE 3

Organizational Chart

FIGURE 4

Basic Concepts for Power Conditioning Development

FIGURE 5

COST PROJECTION OF POWER CONDITIONING SYSTEMS

NEW SOURCE TECHNOLOGIES	PURPOSE		FISCAL YEAR			
			1980	1985	1990	1995
PV & WIND	RESIDENTIAL CATEG. 1		\$1000/KW	\$200/KW → \$150/KW		
			x	(x)		
	LOAD CENTERS CATEG. 2		\$750/KW		\$150/KW → \$100/KW	
			x		(x)	
	CENTRAL POWER CATEG. 3		\$250/KW		\$60/KW → \$50/KW	
			x		(x)	
FUEL CELL	CATEG.	1	\$900/KW	\$200/KW → \$150/KW		
			x	(x)		
	CATEG.	3	\$250/KW		\$60/KW → \$50/KW	
			x		(x)	
BATTERIES	CATEG. 3		\$250/KW	\$60/KW → \$50/KW		
			x	(x)		

x CURRENT COST
 (x) COST GOALS
 COSTS IN 1978 DOLLARS

Supplement to:

IMPLICATIONS OF NEW TECHNOLOGY ON
POWER CONDITIONER DESIGN

BY

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WESTINGHOUSE ELECTRIC

IMPLICATIONS OF NEW TECHNOLOGY ON POWER CONDITIONER DESIGN

- Why is New Technology Needed?
- Is This an Important Problem?
- In Which Areas Can New Technology
by Expected?

NEED FOR NEW TECHNOLOGY

**To Minimize the TPV of Capital and O & M Cost Per kWh
of Energy Generated by Trading Off;**

- **Capital Cost**
- **O & M Cost**
- **Performance**

IMPORTANCE OF PROBLEM

Approximate Breakdown of System Capital Costs for the
1990 - 2000 Time Period When the Cost of the Solar Panels
Drops to 10 to 20 ¢/W

<u>Subsystem</u>	<u>RPS</u>	<u>CPS</u>
Power Conditioner	12%	28%
Solar Panels	23%	26%

NEW OR IMPROVED TECHNOLOGY

Circuit Design

- Self-Commutated Circuits
- Line-Commutated Circuits
- Active Filters

NEW OR IMPROVED TECHNOLOGY

Semiconductor Devices

Improved Devices

- Transistors
- Thyristors

New Devices

- Reverse Conducting Thyristors (RCT)
- Asymmetrical Thyristors
- Gate Assisted Turn-Off Thyristors (GATT)
- Gate Turn-Off Thyristors (GTO)
- Power Field Effect Transistors (FET)

Dwg. 1702879

Conventional

(Many Devices/Wafer)

CBE

	Region 1 Anode Emitter	Region 2 n-Base	Region 3 p-Base	Region 4 Cathode Emitter
Doping Concentration	P_1	N_2	P_3	N_4
Thickness	W_1	W_2	W_3	W_4
Lifetime	τ_1	τ_2	τ_3	τ_4
Resistivity	ρ_1	ρ_2	ρ_3	ρ_4

Fig. 1 — Structure of a thyristor

Trade - off relations

GATE ASSISTED TURN-OFF THYRISTOR

FAST VOLTAGE BLOCKING RECOVERY BY APPLYING
NEGATIVE GATE CURRENT AT ANODE CURRENT ZERO

Fig. 1

Fig. 2-1—Switching current-voltage wave-forms of GCS when using a current source as the gate drive

NEW OR IMPROVED TECHNOLOGY

Magnetic Devices

Amorphous Magnetic Material with the Potential for:

- Lower Losses
- Reduced Manufacturing Cost

Loss as a function of induction, for sinusoidal flux, for amorphous Fe₈₀B₂₀ and some commonly used iron-based magnetic materials. M-4 is grain-oriented; the other commercial alloys are not

NEW OR IMPROVED TECHNOLOGY

Logic and Control

- Greater Use of Microprocessors
- Advanced Microprocessors
- Improved Power Device Modulation
- Improved Output Regulation
- Data Logging
- P.C. Self-Diagnostics
- Unified P.C. and System Control in Smaller Systems
- Unified P.C. and System Self-Diagnostics in Smaller Systems
- Fault Annunciation and Indication

OPTIMIZATION OF DESIGNS USING NEW TECHNOLOGY

- **Computer Analysis of Circuit Performance**
- **Computer Analysis and Prediction of PC Reliability**
- **Computer Simulation of PC Performance in System Applications**
- **Cost/Performance/Reliability Tradeoffs**

EFFECT OF NEW TECHNOLOGY ON PRODUCTION
COST REDUCTION

- Hybrid Logic Packages
- VLSI Logic Modules
- Customized Integrated Hybrid Power Devices

Supplement to:

POWER CONDITIONING FOR LOW
POWER APPLICATIONS

BY

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NASA/LERC

SERI / SANDIA
Power Conditioning Workshop
For Alternate Energy Technologies
May 9 - 10 , 1979

POWER CONDITIONING FOR LOW POWER APPLICATIONS

George O'Sullivan
Abacus Controls Inc.

Roy L. Pickrell
NASA Lewis Res. Cntr.

RELATION OF SMALL PV SYSTEMS TO OVERALL DOE PV PROGRAM

- REMOTE SMALL PV SYSTEMS ARE FIRST TO ACHIEVE ECONOMIC FEASIBILITY

Earliest applications in locations where replenishment of conventional fuel or chemical batteries is difficult, time consuming, and expensive.

Example: Ranger Lookout Stations

- EARLY PV INSTALLATIONS ARE DC STAND ALONE SYSTEMS

Consist of the Solar Array, DC Bus Regulator, Battery, Load and Load Control

- FOLLOW ON INSTALLATIONS MAY BE EXPANDED DC SYSTEMS, AC SYSTEMS OR COMBINATIONS.

Economic TradeOffs will ultimately dictate final configurations.

- SMALL PV SYSTEMS PROVIDE EARLY OPPORTUNITY TO TEST MARKET FEASIBILITY

TECHNICAL CONSIDERATIONS IN BASIC DC PV SYSTEMS

1. EFFECT OF TEMPERATURE VARIATION ON SOLAR ARRAY PERFORMANCE AND IMPACT ON OPERATING POINT OF THE BATTERY STABILIZED DC SYSTEM
2. TYPE OF BATTERY DISCHARGE CYCLE AND EFFECT ON DESIGN OF SYSTEM
 - Annual Deep Cycle with small daily cycle superimposed and where continuous service is provided.
 - Daily Deep Cycle where energy storage is used to extend useful service period.
3. EFFECT OF BATTERY TEMPERATURE ON PERFORMANCE.
4. ARRAY / BATTERY CAPACITY TRADE OFF ANALYSIS WHICH SHOWS EQUAL PERFORMANCE AND POTENTIAL COST IMPLICATIONS.
5. ALTERNATE METHODS OF LIMITING DC BUS VOLTAGE TO PREVENT BATTERY OVERCHARGE.
6. METHODS OF DETERMINING BATTERY STATE OF CHARGE
7. LOAD MANAGEMENT SYSTEM REQUIREMENTS.

TYPICAL DC BUS IV CURVE

TYPICAL SEASONAL EFFECTS

VARIATION OF CELL TEMP WITH SEASONS

Computer program
Data Set

3.5 Kw Array
2308 AH Battery (100 A Rate)
172 AH Annual daily avg array current
154 AH " " " Load Current

TYPICAL BATTERY CURRENT - VOLTAGE RELATIONS
 VARIATIONS WITH STATE OF CHARGE
 (TYPICAL SOLAR ARRAY IV CURVES SUPERIMPOSED)

TECHNICAL DESIGN FACTORS IN SMALL POWER INVERTERS

- BASIC DESIGN REQUIREMENTS NOT A FUNCTION OF SIZE , BUT APPLICATION
- IF STAND ALONE APPLICATION , INVERTER MUST :
 - Be self Commutated
 - Be sized to accomodate load , including providing motor starting currents
 - Be able to supply reactive load currents
 - Provide voltage regulation to accomodate changes in the input DC levels
 - Generate output voltage with harmonics content limited to the Load THD reqs
- IF OPERATED IN UTILITY LINE CONNECTED MODE , INVERTER MUST :
 - Incorporate power level control. Inverter sees utility as essentially a zero impedance load to basic frequency voltages. Power level must be set by a control function , to be compatible with power source capability.
 - Provide for reactive power capability compatible with the power level control mode chosen.
 - Limit harmonic content of current to values acceptable to utility
 - Provide acceptable power factor output

DESIGN FACTORS CONT :

- **PROVISION FOR EQUIPMENT AND PERSONNEL SAFETY MUST BE MADE**
- **DESIRABLE FEATURES FOR EITHER MODE OF OPERATION INCLUDE :**
 - Low losses (high efficiency) during the period when solar array costs are high**
 - Low no-load losses if inverter is to be operated for long periods at low loadings.**

RESPONSE TO DESIGN REQUIREMENTS IN ABACUS 10 KVA INVERTER

- DESIGNED FOR GENERAL APPLICATION. HENCE CAN OPERATE IN EITHER STAND ALONE OR UTILITY MODE
- EFFICIENCY ABOUT 90% FOR LOADS FROM 35% TO FULL LOAD AT NOM VOLTAGE
- NO LOAD LOSSES LIMITED TO 2% to 3% OF FULL LOAD FOR RATED INPUT VOLTAGE
- INCORPORATES POWER LEVEL CONTROL TO SET POWER TRANSFERRED TO THE UTILITY AT THE ARRAY MAXIMUM POWER CAPABILITY
- OUTPUT CURRENT TO UTILITY IS KEPT IN PHASE WITH UTILITY VOLTAGE.
HOWEVER INVERTER IS CAPABLE OF SUPPLYING REACTIVE CURRENT IN EITHER MODE
- OUTPUT CONTACTOR CONTROLLER AND INVERTER BRIDGE DRIVE CONTROLS ARE DESIGNED TO PROTECT AND INTERRUPT SERVICE FOR OUT OF TOLERANCE CONDITIONS'

EFFICIENCY AND LOW NO-LOAD LOSS DESIGN

- USE TRANSISTOR OUTPUT POWER STAGES' OPERATE NON SATURATED
- USE PROM STORED PULSE PATTERN FOR WAVE SYNTHESIS. ELIMINATES HARMONICS IN SINGLE BRIDGE UP TO THE ELEVENTH
- USE DUAL BRIDGE WITH DIFFERENT PULSE PATTERNS TO ELIMINATE HARMONICS UP TO THE NINETEENTH
- HIGHER HARMONIC OUTPUT REDUCE FILTER REACTIVE VOLT AMPS , WITH ASSOCIATED REDUCED LOSSES AT NO NO LOAD
- OPERATE OUTPUT TRANSFORMER AT LOW FLUX DENSITY OF 10 KILOGAUSS FOR REDUCED CORE LOSSES

POWER LEVEL CONTROL (IN UTILITY MODE)

- BASIC POWER LEVEL CONTROL METHOD IS TO SET THE MAGNITUDE OF THE INVERTER OUTPUT CURRENT TO THE UTILITY IN RESPONSE TO A COMMAND FROM THE POWER SYSTEM CONTROLLER (MAX POWER TRACKER)
- THE PHASE LOOP CONTROL MAINTAINS THE OUTPUT CURRENT IN PHASE WITH THE UTILITY VOLTAGE OR AT UNITY POWER FACTOR
- THE CURRENT AND PHASE LOCK CONTROLS ARE INDEPENDENT CLOSED LOOP CIRCUITS BUT INTERACTIVE
- THE CURRENT LEVEL COMMAND IS DERIVED FROM ANALYSIS OF A POWER DITHER SIGNAL AND ESSENTIALLY CAUSES THE INVERTER TO LOAD THE ARRAY TO A TARGET TERMINAL VOLTAGE COMPATIBLE WITH ARRAY MAX POWER

INVERTER CIRCUIT PROTECTION

- LOAD INTERFACE PROTECTION IS PROVIDED BY OPENING OUTPUT CONTACTORS FOR OUT OF TOLERANCE CONDITIONS OF UV / OV ON THE AC LINE
- IN THE UTILITY MODE , CLOSURE OF THE OUTPUT CONTACTOR IS INHIBITED BY OUT OF LIMIT CONDITIONS AT THE INVERTER / LINE VOLTAGE / PHASE COMPARISON
- POWER TO THE BRIDGE DRIVE CIRCUITS LOGIC IS INTERRUPTED BY TRANSISTOR SWITCH FOR OUT OF TOLERANCE VOLTAGE CONDITIONS AT THE INVERTER DC INPUT .
- INVERTER OUTPUT CURRENT IS LIMITED TO SAFE LEVELS BY A CURRENT MONITOR CIRCUIT WHICH OVERRIDES ALL OTHER SIGNALS IF CURRENT REACHES THE PRE SET CURRENT LIMIT

INVERTER VOLTAGE AND CURRENT TRACES

Inverter voltage at 10 kw
in stand alone mode

Line voltage and inverter
current at 10 kva to Utility

PHASE LOCK ACQUISITION

Torque Angle Trace : Angle between Inverter internal voltage & Line V

LOSS OF PHASE LOCK AT 10% LOAD

Inverter voltage 240 V RMS

Inverter current 4A RMS

FIELD TEST at LEWIS RES CNTR INVERTER OPS - UTILITY MODE - SOLAR ARRAY POWERED

Vary PSC command to regulate SA at different voltage levels

TECHNICAL APPROACH TO LOWER COST POWER CONDITIONER

- TARGET CALLS FOR \$200 / WATT COST FOR SINGLE PHASE 10 KVA X FORMER
- ABACUS DESIGN COMBINES SIMPLE SCR / TRANS FORMER WITH CONTROLLED FERRO RESONANT TRANSFORMER TO ACCOMPLISH DC TO AC CONVERSION
- OUTPUT VOLTAGE PHASE SET BY SCR INVERTER TO MAINTAIN OUTPUT CURRENT IN PHASE WITH UTILITY
- OUTPUT POWER LEVEL SET BY CONTROLLED FERRO RESONANT X FORMER BY OUTPUT CURRENT AMPLITUDE CONTROL
- FILTERING IS ACCOMPLISHED BY THE FERRO RESONANT TRANSFORMER

ADVANCED 10 Kva INVERTER CONCEPT

CONTROLLED FERRO RESONANT TRANSFORMER

SCHEMATIC DIAGRAM
CURRENT FED SCR INVERTER

PV - PWR CONDITIONING DEVELOPMENT : BACKGROUND

- SURVEY EARLY IN PROGRAM INDICATED THAT THERE WERE NO " OFF THE SHELF " HARDWARE SUITABLE FOR PV APPLICATIONS
- EARLY PV APPLICATIONS WERE MOSTLY DC, HENCE DID NOT REQ' PWR COND'
- PLANNING ACTI VITY BY SANDIA : MIT : AND LeRC DEFINED NEED FOR ORDERLY DEVELOPMENT OF GENERAL PURPOSE POWER CONDITIONERS , CUSTOMIZED FOR PV APPLICATIONS.
- ORDER FOR DEVELOPMENT OF SMALL 10 KVA PV INVERTER PLACED BY LeRC WITH ABACUS CONTROLS. FOLLOW ON UNIT MODIFIED BY SANDIA CONTRACT FOR MAX PWR TRACK CAPABILITY' CONTRACT STRESSED PERFORMANCE
- DEVELOPMENT OF 50 KVA PV INVERTER PLACED BY SANDIA WITH WESTINGHOUSE UNIT ALSO STRESSED PERFORMANCE

PV - PWR: CONDITIONING CONTINUED:

- DEVELOPMENT OF ADVANCED 10 KVA INVERTER PLACED BY SANDIA WITH ABACUS . STRESSED COST GOALS
- DEVELOPMENT OF 60 KVA INVERTER PLACED BY MERADCOM WITH DECC: INCORPORATED MAX PWR TRACKING
- DEVELOPMENT OF FAMILY OF SMALL (0.5 TO 3 Kw) INVERTERS BY
- INDEPENDENT DEVELOPMENT OF SMALL INVERTERS STRESSING LOW LOSS OPERATION MADE BY SMALL FIRMS

TECHNICAL AREAS - REQUIREMENTS

- DEVELOPMENT OF INVERTER SPECIFICATIONS BY SERIAL
- EFFICIENCY - GOALS - HOW TO MEASURE
- INPUT VOLTAGE RANGES - DIFFERENT FOR BATTERY STABILIZED BUS
- OUTPUT VOLTAGE LIMITS
- FREQUENCY STABILITY
- OUTPUT HARMONIC CONTENT - HOW MEASURED

WHAT MARKETS TO ADDRESS

- EARLY STAGE OF PV INDUSTRY MAY PROMOTE SMALL INVERTERS AS FIRST TO BE ECONOMICALLY FEASIBLE. SPEC TOLERANCES MAY BE LOOSE.
- MEDIUM SIZE UNITS MAY BE FEASIBLE FOR REMOTE VILLAGES OR COTTAGE INDUSTRY
- INTERFACE WITH UTILITY NETWORK PROBABLY WILL GENERATE MOST RIGOROUS SPECIFICATIONS

DC APPLICATIONS

- IMPRACTICAL TO USE SOLAR ARRAY OUTPUT DIRECT IN MOST APPLICATIONS BECAUSE OF WIDE VARIATION OF VOLTAGE WITH LOAD
- BATTERY SERVES TO STABILIZE BUS VOLTAGE
- VOLTAGE REGULATION MAY BE LIMITED TO PROTECTING THE BATTERY FROM EXCESSIVE CHARGE
- MAX POWER TRACKING COULD INCREASE POWER OUTPUT BUT MAY NOT BE ECONOMIC
- DEVELOPMENT OF DC EQUIPMENT FOR DOMESTIC USES MAY BE NEEDED IN ORDER TO FULLY EXPLOIT PV POWER SOURCE'

COST CONSIDERATIONS IN PV SYSTEMS

- **CURRENT COSTS FOR SMALL PV SYSTEMS ARE ABOUT \$30/WATT.**
Costs about equally divided between modules and balance of system (BOS)
- **COST EFFECTIVE APPLICATIONS JUSTIFIED FOR ONLY A LIMITED FEW CASES**
Little incentive for sophisticated systems. However, improved efficiency can sometimes pay off in reduced array requirements. Example: A 10% increase in BOS efficiency can reduce array costs \$1.50 / Watt at current array costs.
- **WHEN ARRAY COSTS ARE REDUCED TO THE DOE PROGRAM GOALS OF \$1 / WATT**
BOS COSTS CAN BE THE IMPEDIMENT TO COMMERCIAL FEASIBILITY.
- **TRADE OFFS, BASED ON ELEMENT COSTS MAY BE USED TO OPTIMIZE SYSTEM COSTS FOR EQUAL PERFORMANCE**

Working Group 1

POWER CONDITIONING FOR PHOTOVOLTAICS

POWER CONDITIONING FOR PHOTOVOLTAICS

Group Report
Roy Pickrell, Leader
NASA Lewis Research Center
Cleveland, OH

INTRODUCTION

The overall DOE goal for photovoltaics is to promote the implementation of photovoltaics as a viable alternative energy source. The power conditioner is a key element in a photovoltaic system. Thus, to achieve the DOE goals, power conditioners must be developed which meet certain performance standards and which can be mass produced at sufficiently low cost. The purpose of this working group was to assess the current technology in power conditioning for photovoltaic systems, to identify operational requirements, to identify problem areas, and to obtain inputs which will be useful to DOE in planning future activities. The working group included 48 persons from government, private industry, utilities, and universities. The detailed breakdown was as follows:

Government	11
Universities and Private Labs	8
Solar Array Manufacturers	7
Power Conditioning Manufacturers	6
Potential Customers	5
Utilities	3

The chairman of the group was R. Pickrell of NASA Lewis Research Center. Panel members included:

George O'Sullivan	Abacus Controls
Ervin Lyon	MIT Lincoln Labs
Frank Goodman	L. A. Dept. of Water and Power

E. Landsman

MIT Lincoln Labs

Hans Meyer

Windworks

Discussion Topics

The major topics of discussion were projected costs, power quality, and the direction for future development activities. Other topics briefly discussed included possible size limitations of photovoltaic systems and general safety issues for dispersed power systems. The following is a synopsis of the discussions.

a) Projected Costs - Consumer cost projections by several contractors who are developing power conditioning units for photovoltaic systems were presented. All were within the DOE cost goal of \$200/kW in production quantities of several thousand units per year. The question was raised whether or not a real market for a residential type 10 kVA unit would exist at this cost, i.e., is the residential market a viable application? It was noted that a \$1600/kW installed total system cost is viable if the value of power produced is 5-7¢/kWh. Within that context \$200/kW for the power conditioner is a reasonable fraction of the total cost. It was also stated that the \$500/kW production goals for PV modules by 1986 will be met if annual production rate is 50 MW/yr, corresponding to 5000-6000 houses per year.

The validity of the \$200/kW projected costs was questioned by some, but it was supported by firm price quotations for all materials and labor estimates based on current labor and burden rates. One manufacturer gave the following approximate cost breakdown for his dual bridge transistorized 10 kVA unit, including labor:

Transistors	44%
Sheet Metal	26%
Magnetics	13%
Switchgear	13%
Logic, Low-Level Electronics, and Miscellaneous	4%

Another vendor who manufactures line commutated inverter systems in this power range itemized his costs as follows:

Filters	39%
Power Train	26%
Control	9%
Contactors	5%
Cabinet	5%
Miscellaneous	7%
Labor	9%

b) Power Quality - Discussion of this topic began with attempting to define acceptable values of harmonic distortion and power factor. One participant pointed out that the utility line impedance should be defined in order to establish a power quality standard. Another suggested that harmonic content of the current injected into the utility line should be the basis for a power quality definition. An oscilloscope trace of the current from a 10 kVA inverter injected into the utility line was presented; the measured current THD was 3.6% for full load operation.

The Europeans have developed a specification identified as UDE which addresses the question of injected noise, but no comparable U. S. standard exists. One participant pointed out that

insistence on power quality standards for photovoltaics where none exist could unduly penalize power conditioner costs. However, strong concern was expressed by the utility representatives on the potential problems of noise injected onto the utility lines by customers, no matter what the source. In fact, they indicated a feeling of responsibility to protect other customers from excessive injected noise and stated that they were in the process of establishing a consensus relative to that problem.

c) Direction of Future Development Activities - The feasibility of achieving further cost reductions to produce photovoltaic power conditioners in the 10 kVA range which could sell for \$100/kW was discussed. New components such as gate turn off SCRs and low cost transistors with greater power handling capability may in the future bring about significant cost reductions. Amorphous magnetic materials may make it possible to reduce the cost of transformers and inductors. Circuit development activity should be geared toward innovative designs which take advantage of available circuit components. In particular, the use of a high frequency link to eliminate the heavy, costly 60 Hz magnetic components is a technique worthy of renewed investigation. A development effort for lower cost DC switchgear was also encouraged. An issue which needs to be resolved is the safety and stability of a number of dispersed power systems connected to the utility grid, and the effects of harmonics in such systems.

d) Other Topics Discussed

1) The subject of power conditioning for dc systems was discussed briefly. It was agreed that, as a minimum, some

form of bus voltage regulation would be required to limit battery charge voltages.

2) The efficiencies of power conditioners developed for photovoltaics are typically 90% or better for 50 to 100 percent load. One manufacturer reported tare power losses of 5 to 7 percent of full load for a 10 kVA SCR bridge device with a controlled ferroresonant transformer; he compared this to 2 percent for his 10 kVA dual bridge transistor unit.

3) The question was raised whether 10 kVA is the only size required for residential applications. One manufacturer plans to develop a low cost product line which includes 6, 10, and 15 kVA sizes.

4) A chart (attached to this summary) was presented showing the results of a preliminary dc cable size/cost/loss analysis performed by GE for a variety of power levels with dc bus voltage as a parameter. The results would appear to indicate that, in order to limit the dc cable power losses to a few percent it is necessary, for systems of a size greater than about 100 kW, to either

a) operate at dc voltages greater than those at which most present arrays are designed to operate, or

b) break up the array into modules with separate inverters for each module. However, the critical system size is several MW if one considers energy losses rather than power losses in the dc cable.

Although present arrays are tested at 1500 volts, they are operated at only a few hundred volts at most. For comparison it was noted that fuel cell power conditioning units operate at 265 volts, and a 4.8 MW unit for battery systems operates

at 3400 volts.

5) There are currently no requirements for isolation of a photovoltaic (or other alternative energy) system from the utility although many proposed systems include an isolation transformer. Similarly, there are no requirements for grounding arrays. Grounding provisions similar to those for battery systems might be suitable, except that photovoltaic arrays have the added disadvantage of being located outdoors and thus must also be protected from lightning strikes.

CONCLUSIONS AND RECOMMENDATIONS

Future development activities for power conditioners for photovoltaic systems should be directed toward innovative designs which reduce the cost, with production goals of \$100/kW or less for the 10 kVA size. These designs should minimize raw materials and take advantage of available, low cost components. New developments in solid state devices and magnetic materials should be noted, particularly as other markets bring about cost reductions. The possibility of initiating a program to develop low cost dc switchgear should be considered. Finally, a computer study should be initiated to analyze the mutual interaction of a large number of residential photovoltaic or other dispersed power systems connected to a utility grid. Such problems as stability, harmonics, cloud cover (for photovoltaic systems), and safety should be included in the analysis. This should be followed by an applications experiment, e.g., a housing development with photovoltaic power systems connected in parallel with the utility, to obtain data and compare it to the computer analysis.

Working Group 2

**POWER CONDITIONING FOR FUEL CELLS AND
BATTERY STORAGE**

WORKING GROUP ON POWER CONDITIONING
FOR FUEL CELLS AND BATTERIES

Paul F. Pittman, Group Leader

Summary

1. Introduction

The purpose of the group was to discuss the following topics in regard to power conditioning for fuel cell and battery energy systems:

- Assess current and future technology
- Identify operational requirements
- Identify mass production and marketing requirements
- Suggest effective ways to stimulate development

The discussion period allocated for the work of the group was subdivided into four parts, and a period of time was devoted to discussion of each of the major topics listed. In the case of some, the discussion was quite detailed, while others were omitted entirely either because they were irrelevant to the work of the group, or because there was no time for their consideration.

The group was quite diverse, comprising twenty people including 13 from industry, four from government, and three from utilities. The 13 from industry included battery vendors, fuel cell vendors, power conditioner vendors, and users of such equipment. Because of the diverse backgrounds of the group members, a stimulating and effective dialog was set up between energy source vendors and power conditioner vendors which was of benefit to all working group attendees.

2. Discussion Topics

A few basic assumptions were made to lay the ground work for the discussion of the group and to limit the range of the discussion to one commensurate with the available time. The time period considered for the discussion ranged from the present to the year 2000.. When projections were made, the discrete points of the present, 1985 and 2000 were used where appropriate. In addition, in the case of battery systems, only battery energy storage systems were considered. Hybrid systems which included batteries together with alternative energy sources, such as photovoltaic array, were excluded.

2.1 Technology Assessment

It was determined that the basic power conditioning technologies needed for battery and fuel cell systems are quite similar. The equipments needed differ at the input or DC interface because of the differing characteristics of the two types of energy sources, while the output or AC interfaces are quite similar. A major difference in performance is the need for bidirectional power flow in the battery power conditioner which is not required for the fuel cell power conditioner.

For the purposes of the discussion of this group, the following ranges of operating power level were established:

Batteries	2.5 MW to 100 MW
Fuel Cells	50 kW to 100 MW

Present technology is best described in terms of existing programs as follows:

2.1.1 Batteries - The largest battery program now in progress is the BEST facility which includes construction of a developmental lead acid utility load levelling battery facility capable of 2.5 MW at a 5 hour rate. A new, large commercialization program about to be started is the SBEED program which will also be a utility load levelling battery which will provide 20 MW at a five hour rate.

Both line-commutated and force-commutated inverters have been used for such systems, and both are under consideration for future applications. The group could not reach a concensus on this point because the choice is largely a matter of personal preference at this time. Each system has its performance advantages and disadvantages as well as development and production costs, all of which must be weighed for each application.

At present, only lead acid battery systems are available for system development and commercialization, but many other systems are in the R&D stage and should begin to become available for system development by 1985. Included are ZnCl_2 , ZnBr , NiH , LiFeS , NaS , and Redox. Although the power conditioning needed for these advanced systems will be basically the same as that used for lead acid systems, some have certain special requirements which should be studied at this time so the necessary equipment will be available when needed.

The circuit breakers used for large DC systems are the largest available. A 5000A breaker made by Siemens is being used for the BEST facility, but larger units are needed and maintenance is a problem. Westinghouse has an EPRI contract to develop a 2500A breaker, but it works in conjunction with the power conditioner and is not an in-line interrupter.

A consideration in breaker design is the surge current capability of the energy source. The fuel cell is current limited, but can produce a short, high amplitude pulse of current. Conventional lead acid batteries can produce surge currents 10 to 20 times rated, while newer battery systems produce surge currents only two to three times rated.

Analytical models of presently used lead acid batteries needed to describe both transient and steady state battery performance are hard to obtain. If better models were available, better power conditioner design could be performed, and equipment testing would be simplified. In general, the power conditioner can be designed to provide the kind of performance desired if the performance requirements are made known. Needed are requirements for charge and discharge as well as startup, standby, and shutdown.

The battery for the BEST facility includes 500 cells in series yielding 1000V. Equilization is accomplished by overcharging the battery causing the cells to gas. The resulting hydrogen is then driven from the battery building by a fan. From the standpoint of the power conditioner, the number of series cells and thus the resulting DC output voltage should be higher, in the order of 2000 to 3000V. The impact of such a change on battery cost and performance should be investigated.

The present battery module size is 5000A leading to a 5 MW module. The size is determined by a number of constraints including the size of the largest DC breaker available. It is possible that this size is optimum, but further work should be done to verify this or to recommend a more optimum module size.

2.1.2 Fuel Cells - The state of the art in fuel cells at present can be characterized by the major installations which are a unit at Consolidated Edison rated at 4.8 MW, and several smaller units rated at 40 kW to 120 kW.

Owing to a shortage of time, the fuel cell technology assessment discussion was cut short.

2.2 Operational Requirements

The following operational requirements were discussed.

Power Quality - The quality of power required by the utilities has not yet been defined, but a number of EPRI programs include an investigation of factors relating to it. A partial list of these is as follows: RP 1024-1, RP 841-1, RP 390, and RP 840. A contributing document is the IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters.

Reliability - Availability is one measure often used. In DC transmission systems, values for Av exceed 96%. For battery and fuel cell systems, the availability goal should be a minimum of 95%. The predicted availability for SBEED is 99%

The FAA has deployed 90 UPS systems at airport control towers throughout the country. After two years of experience, the observed mtbf is in excess of 17000 hrs.

When equipments are designed, analyses of the affects of single point failures should be conducted. In present large systems, power transformers present a common failure problem. The failure of a large transformer usually has a severe effect on system performance, and is costly and time consuming to replace.

Efficiency - The following power conditioner performance goals were established. Efficiency should be greater than 96% at full load, and greater than 92% at 1/4 load. Presently attainable efficiencies for HVDC systems are in excess of 98%.

Cost - The cost goal for battery and fuel cell power conditioners established by DOE and EPRI for 1985 (in terms of 1975\$) is \$60/kW for systems of the order of 10 MW in quantities of at least 150/yr. This goal is the FOB price from the vendor. By the year 2000, the goal reduces to \$50/kW.

Safety - Both AC and DC fuses must be coordinated. Potential problem areas must be analyzed separately such as the possibility of flash fires from oil used in capacitors and transformers.

Testing - Smaller systems can be tested at the vendor's factory, while larger systems can be field tested only as is the case with HVDC terminals. Factory testing is difficult because a true battery or fuel source is generally not available and accurate source simulation is difficult. Furthermore, handling the large power flows involved can be a problem leading to the establishment of synthetic testing procedures. One of the purposes of the BEST and SBEED programs is to provide a test facility for both batteries and battery power conditioners.

Large system builders have found that in many cases, control circuit testing and debugging is more time consuming and costly than power pole testing.

3. Conclusions and Recommendations

- Workers in the field should make better use of published information and reports. Better ways should be found to disseminate knowledge generated.
- Efficiency, performance, and cost goals appear reasonable. Industry can only be assured that they can meet these if a market appears and units are built and sold.
- System related issues, such as availability, mtbf, and maintenance should be addressed in greater depth.
- The DOE/EPRI battery and fuel cell programs as presently defined appear to be reasonable. The goals specified should be pursued.
- The SBEED program should proceed as defined with a heavy involvement of both DOE and EPRI with the EPRI participation defined more precisely.
- DOE, industry, and the utilities must obtain a better appreciation for each others goals motives and objectives so that programs can be defined in a more effective manner to the benefit of all concerned.

Working Group 3

**POWER CONDITIONING FOR WIND AND OTHER
TECHNOLOGY**

POWER CONDITIONING FOR WIND AND OTHER TECHNOLOGIES

L. C. Mrig
Solar Energy Research Institute

Approximately 20 people attended the morning session on the power conditioning for wind and other technologies. These people represented a broad cross-section of industry, utilities, R&D institutions and an independent consulting engineer. The discussion was quite informal, informative and stimulating. Everyone present did contribute to the discussion and gave their inputs to the session.

There were two speakers from the industry who made informal presentation to the group. The first speaker was Hans Meyer from Windworks and he discussed the line commutated inverter system for a grid connected wind energy conversion system. There are about 145 installations already for Gemini Synchronous Inverters and most of them are wind applications. The cost, performance and interconnection issues for this type of utility interface were addressed. According to him, the cost and efficiency goals for power conditioning in photovoltaics are presently achievable in mass production volume. However, it was mentioned that at present there are no power conditioning cost and performance goals established for the wind energy conversion systems although 10% of the total installed cost for the small wind energy conversion systems is considered to be a good goal for power conditioning equipment. It would help if Wind Systems Branch of DOE would establish some goals for power conditioning equipment for the manufacturers to go by in the wind area.

The next presentation was by Bob Barton of General Electric Company, Space Division. He talked about 2 MW MOD-1 Boone, N.C. installation. This synchronous machine is connected to the distribution network and as far as the power conditioning for this large machine is concerned, the excitation control for the generator and speed and

torque control were the key items that were discussed.

Most of the large wind machines in this country are either AC induction generators or synchronous generators and as such there is no power conditioning involved in them, although in Europe there is some work being done in the area of power conditioning for large machines by going to the scheme of DC generator and inverter thus capturing some more energy at some added costs.

The discussion then went on to the question of identification of potential markets for power conditioning for wind applications and it centered on the question of grid connected wind energy conversion system vs. dispersed stand-alone applications. The point was brought out that there is no clear answer as yet to whether the grid connected Wind Energy Conversion Systems is the coming near term market or stand-alone application is the near term market and people present had different views on this subject and it was felt that the outcome of this issue based on the uncertain potential consumer preferences will have an impact on the role of power conditioning in the wind area. It was suggested that an economic analysis of both the markets should be undertaken to resolve the issue.

The question of safety and reliability was discussed briefly and there was no consensus on whether the consumer is liable for the safety of equipment and personnel or whether the utility is responsible, although it was generally agreed that utilities more likely will not get involved in the operation and ownership of small wind energy conversion systems.

On the question of improvements needed in the power conditioning in the wind area it was obvious that the requirements for power conditioning equipment have not yet been standardized, and at present these requirements vary from installation to

installation and from utility to utility. What needs to be addressed in this area by DOE and R&D institutions is to develop a set of standards in coordination with the utilities which would let the consumer know what the power conditioning and utility interface requirements are and it will also, to some extent, standardize the technical specifications to be met by power conditioning industry. It was suggested that a set of specifications could be applicable to the stand-alone applications and another set of standards could be applied to the grid-connected power conditioning equipment. I think this was one of the major outcomes of this session.

The issue that was raised several times and remained unresolved was regarding what R&D work needs to be done now in the area of power conditioning for the wind systems and it was thought that the bigger issue to be addressed is the identification of major applications of wind energy conversion systems and once it is identified that a substantial market exists for stand-alone applications which require power conditioning, the industry would then be willing to put money in the R&D of power conditioning and most of the technical problems expected to be encountered are solvable by engineering although they will affect the cost of the wind energy conversion system. Rocky Flats program of installing 125 small wind machines over the U.S. will shed some light in this area.

In the area of other technologies besides wind, some of them were discussed in general, but no discussion was held in the area of power conditioning as applicable to those technologies.

In summary then, three recommendations that come out of this session were:

1. The need for identification of potential markets in the wind area requiring power conditioning.

2. Establishment of cost/performance goals by DOE Wind Systems Branch for power conditioning in the wind area.
3. Development of a set of standards needed in the power conditioning and utility interface areas to be developed with the cooperation of utilities which would benefit both the users and the manufacturers alike.

In the end, I would like to thank all the participants for a meaningful interchange of valuable information. Thank you!

WINDWORKS, INC.

POWER CONDITIONING ENGINEERING PROGRAM

HANS MEYER

INTERCONNECTION ISSUES

LOW PENETRATION

- SAFETY
- ECONOMICS

HIGH PENETRATION

- POWER QUALITY
- POWER OUTPUT PREDICTION
- POWER HANDLING

LINE-COMMUTATED INVERTER

ADVANTAGES

- LOWER SYSTEM STRUCTURAL LOADS
- HIGHER SYSTEM ENERGY OUTPUT
- SIMPLIFIED ROTOR CONTROLS
- HIGHER ROTOR SPEEDS
- HIGH GENERATOR EFFICIENCIES
- GOOD AVAILABILITY

DISADVANTAGES

- HIGHER POWER SYSTEM COST
- GREATER POWER SYSTEM COMPLEXITY
- LOWER POWER QUALITY
- LOW POWER FACTOR - VARIABLE VARS

INDUCTION GENERATOR

ADVANTAGES

- LOW POWER SYSTEM COST
- POWER SYSTEM SIMPLICITY
- HIGH POWER QUALITY
- GOOD AVAILABILITY

DISADVANTAGES

- HIGHER SYSTEM STRUCTURAL LOADS
- DECREASED ENERGY OUTPUT
- LOWER ROTOR SPEEDS
- LOW POWER FACTOR - CONSTANT VARS
- LOW GENERATOR EFFICIENCY
- HIGHER POWER SYSTEM WEIGHT

LINE INTERFACED PHOTOVOLTAIC ARRAY

LINE INTERFACED PHOTOVOLTAIC ARRAY WITH LOAD CONTROL

LINE INTERFACED PHOTOVOLTAIC ARRAY WITH STORAGE

PEAK SHAVING WITH LINE INTERFACED PHOTOVOLTAIC ARRAY AND BATTERY STORAGE

PHOTOVOLTAIC ARRAY WITH STAND-ALONE LINE COMMUTATED GEMINI INVERTER

GEMINI SYNCHRONOUS INVERTER EFFICIENCY VS CAPACITY

<u>ITEM</u>	<u>EFFICIENCY @ FULL LOAD</u>
BASIC GEMINI	
SINGLE PHASE	96 %
THREE PHASE	98 %
INPUT FILTER	90 - 98 %
OUTPUT FILTER	90 - 98 %

GEMINI SYNCHRONOUS INVERTER COST VS CAPACITY

GEMINI INSTALLATIONS

NO. AMERICAN CONTINENT

145 TOTAL INSTALLATIONS

35 STATES

3 CANADA PROVINCES

VIRGIN ISLANDS

Working Group A

POWER CONDITIONING FOR LARGE SYSTEMS
INTEGRATED WITHIN A UTILITY GRID

POWER CONDITIONING FOR LARGE SYSTEMS
INTEGRATED WITHIN A UTILITY GRID
WORKSHOP SUMMARY

Stanley Krauthamer
Workshop Chairman
Jet Propulsion Laboratory
Pasadena, California

INTRODUCTION

This document represents a summary of the workshop on "Power Conditioning for Large Systems Integrated Within a Utility Grid" prepared by the Workshop Chairman.

With the advent of the rapid development of alternate energy and storage sources the methodology of interfacing this energy into a utility grid provides an interesting challenge. The interfacing power block between the alternate sources and the utility grid is labeled a power conditioner. The alternate energy source and the requirements for interface with the utility grid places certain design and performance constraints upon the power conditioner.

The basic issues dealing with power conditioners were broken down and discussed with respect to the following categories:

- State of Technology
- Available Technologies
- Hardware Availability
- Power Conditioner Costs
- Performance and Operational Requirements
- Requirements to Stimulate Development
- Technology Development Recommendations and Comments

The working group was made up of approximately 24 persons (the exact number varied as several persons rotated between working groups). Included in the above was a panel of six persons, all specialists from private industrial concerns. Thirteen of the group members represented private industrial concerns, three members were from utility organizations, one represented a university and three represented government agencies and national organizations.

The working group was addressed by the Chairman and the six panel members. The discussions were informal in nature and addressed the various relevant systems and power conditioner issues.

STATE OF TECHNOLOGY

Power conditioner technology is a reasonably mature technology. Substantial experience has been gained over the past number of years. Four major areas of power conditioner technology are as follows:

1. Uninterruptible Power Supplies (UPS)
2. AC Adjustable Speed Inverter Drives
3. High Voltage DC Transmission (HVDC)
4. VAR Generators

UPS systems have been produced on a rather extensive scale in the sizes of 15-600 kW. Systems have been built as large as 2.5 MWe with one unit rated at 8 MWe, in process for the Social Security Administration. These systems are generally 3 ϕ types operating at a DC bus voltage of 120 VDC - 600 VDC. Voltage regulation is $\pm 1\%$ and harmonic distortion is 5%. Typical mechanical dimensions for a 600 kW UPS is 7' x 16' x 3'. The inverters are forced commutated types using either six or 12 pulse inverters. The basic problems of parallel operation have been mastered indicating that the typical UPS system has the potential of being connected to the utility bus with provisions for proper logic control.

There are 1000 UPS installations in the U.S. Ten systems are rated at 2.5 MWe. The UPS systems are manufactured on a volume basis and the market for these systems is quite competitive. UPS pricing can be used to arrive at base line costs for large power conditioners for alternate energy sources. UPS units have proved to be highly reliable. On a production run of 90 UPS units for the FAA an MTBF of 17,000 hours was established (Garrett AiResearch).

AC adjustable speed inverter drives have been used for AC motor speed control for the past 20 years. Thousands of these systems, 10 kW - 25 MWe, have been in operation. These systems have been used by textile fiber manufacturers, machine tool manufacturers and the railroad industry. The systems generally operate over a speed range of 6:1 and voltage regulation of approximately $\pm 2\%$. The AC motors operate from low frequencies up through 400 Hz. The systems are generally forced commutated types with either 6 or 12 pulse operation. DC bus voltages range from 100 VDC - 1500 VDC.

High voltage DC transmission (HVDC) systems are used to transmit power over great distances. Generally these systems operate at voltages above 100 kV and powers in excess of 100 MWe. Systems have been in operation in Europe and the U.S. with excellent reliability records. A typical system at Eel River (280 kV) shows a 99% availability and a 96% availability for two units including planned outages. A system with 6000 SCR's (50 mm) had a failure rate of three devices in two years. Redundancy of SCR's in these systems is approximately 15%. The typical systems installed in the U.S. consist of 2-6 pulse line commutated bridges. One bridge in a wye-wye configuration

and one bridge in a wye-delta configuration. This connection offers reduced harmonic distortion. For systems at 100 MWe or below series tuned filters are used to filter the 11th and 13th and higher harmonics.

VAR generators have been developed for use in cleaning up the effects of arc furnaces on the utility line. The VAR generators are line commutated phase controlled inverter switches. They are used as harmonic filters, power factor correction and a means to balance a 3 ϕ line. Total VAR generation capacity is 1200 MVAR. VAR machines are competitive with synchronous condensers and capacitor power factor correction. The VAR generator is basically a controlled inductor in parallel with capacitors usually termed a "Dynamic Steinmetz Balancer".

In recent years substantial efforts have been expended to develop advanced systems for large power conditioners. The three most notable systems are:

1. BEST Facility: A joint effort of DOE, EPRI and PSE&G. This facility is designed to test out advanced electrochemical storage systems for load leveling. This facility is currently being built and should be on line in the 1980 time frame.

Facility operating DC bus will be rated at 500 VDC - 1000 VDC with peak rating at 1000 VDC and 5000 amperes. The system will be under microcomputer control. Inversion technology relevant to this facility has been demonstrated by 1000 hours of operation of an inverter feeding into a utility grid (built by UTC).

2. Consolidated Electric of New York: This system is a joint EPRI, DOE and Consolidated Electric effort. The system is a load leveling system with a fuel cell and inverter supplied by United Technologies Corp. The system rating is 4.6 MWe with a DC bus voltage rated from 2700 VDC to 3600 VDC.
3. SBED: This system is a joint EPRI and DOE program. The program objective is to field and test over a period of nine years a load leveling system rated at 10-20 MWe with electrochemical storage of from 3-5 hours. This system is currently out for competitive bid.

AVAILABLE TECHNOLOGIES

Two technologies are currently used for large power conditioners connected to a utility grid. These technologies are the forced commutated types and the line commutated types. The forced commutated types use external methods to turn off the power SCR devices whereas the line commutated inverters use the utility grid to turn off the power SCR's. There are many advantages and disadvantages for each technology. The characteristics of these systems are available from the various power conditioner manufacturers. Once a number of systems of both technologies are integrated into a utility grid, then a proper

assessment of each system can be made. The market place will be the final determinant as to which technology is technically and cost-wise the most adequate.

HARDWARE AVAILABILITY

Various types of hardware are available either as an off-the-shelf or as a developmental type unit that will interface with a utility grid. Power ratings range from 40 kW to 14 MWe. The optimum systems from a cost point of view are available at 14 MWe from UTC and 12 MWe from Garrett AiResearch. Other vendors will likely have similar ratings. DC bus voltages will range from 2200 VDC to 3800 VDC for optimum costs. It is anticipated that most systems will have microprocessor control for operation purposes and power management purposes.

POWER CONDITIONING COST

Power conditioning costs vary as to technology types, MWe size and available DC bus voltages. Several of these issues are addressed in EPRI Reports RP841-1, 842, 255. Cost projections for advanced 3Ø UPS systems are as follows (DC input-AC output):

KVA	Selling* Price \$/kW
10	500
1 MVA	200
10 MVA	100
15 MVA	85

*1985 time frame (1979 dollars) (Exide Power Systems)

For DC input-AC output systems a cost of \$150/kW for 8 MWe size reflects current prices.

For the advanced technology inverters 14 MWe, 2200 VDC - 3600 VDC inverter costs are \$45/kW at a production rate of 150 units/year (1975 dollars). The cost of the advanced technology inverters can cost from five to 10 times the \$45 when quantities are quite small. It should be noted that inverters below the 14 MWe rating will show increased costs as MWe ratings are reduced (UTC).

HVDC systems are reviewed in EPRI Report RP390 with anticipated costs being \$30/kW. Current market costs reflect about \$100/kW (GE).

PERFORMANCE AND OPERATIONAL REQUIREMENTS

A detailed performance and environmental specification is necessary in order to adequately interface with the generation or storage source and the utility

grid. Generation sources will vary in voltage level. In addition the voltage range of operation will vary according to the generation source and the type of electrical storage if any. Advanced electrochemical storage systems should be clearly defined since a particular charge or discharge cycle may be excessive with respect to the capability of the power conditioner. Generally the power conditioners that have been described are adequately flexible in design so that they can be applied to an extensive range of applications. These applications extend from photovoltaic systems, solar thermal systems, MHD systems, wind systems and load leveling systems.

Efficiency requirements are high in order to have low delivered energy costs. The UPS systems described previously typically have an inverter efficiency of 95% (600 VDC bus). The advanced technology inverters typically have efficiencies of 96% at full load and 92% at 25% load (14 MWe, 2200 VDC - 3800 VDC).

Utility line interface is another area which must be more clearly defined. These efforts for a more clearly specified direction will require the joint involvement of DOE, EPRI, Electric Utilities and Power Conditioner manufacturers. Some of the issues of line interference are addressed in EPRI Report 1024-1. Generally a 5% distortion of voltage or current is acceptable, but as a greater number of dispersed generation and storage units are interfaced with the utility grid, this value will likely be reduced toward 1% total harmonic distortion. Requirements at the Best Facility are 2% maximum harmonic injection.

Performance testing is an area of great importance since it is desirable to system or module test of the power conditioner prior to installation. Various methods for testing were discussed. These varied from calculation of losses for efficiency determinations to circulating module power back to back to supply only the module losses. Microprocessor control can aid in system testing and system trouble shooting. The microprocessor can be utilized as an important diagnostic tool.

REQUIREMENTS TO STIMULATE DEVELOPMENT

During the past several years important technical strides have been made in the development of advanced technology power conditioners. Two areas of support are suggested in order to arrive at optimum cost, efficiency and reliability goals. These areas are:

1. Additional development contracts to improve technology and componentry (see program recommendation and comments).
2. Placement of production contracts for large power conditioners to assist in optimizing cost, efficiency, reliability goals and delivered energy cost goals.

TECHNOLOGY DEVELOPMENT RECOMMENDATIONS AND COMMENTS

During the workshop session various suggestions were made relating to both component and system technology and program direction. These suggestions have been summarized and are detailed as follows:

1. Develop system modeling of delivered energy cost versus component cost.
2. Provide better interface with various component vendors (battery, inverter) contractors and utilities to improve more adequate system engineering.
3. Analyze slew rate of batteries and other energy sources.
4. Review new technology batteries and power sources for unusual interface requirements.
5. Utilities to provide guidance for identification of permissible harmonic levels and utility characterization.
6. For forced commutation inverters the following technology areas would improve system cost, efficiency and protection.
 - A. Operation of inverter with a faulted bridge with higher harmonics.
 - B. Improved commutation capacitor technology.
 - C. Improved DC fusing technology.
 - D. Development of inverters with higher switching frequency for improved harmonic cancellation.
 - E. Advanced packaging and cooling methods.
 - F. Application of microprocessor technology to inverter and system control.
 - G. Improved power conditioner efficiency.
 - H. Snubber circuit technology improvement.
 - I. Improved SCR voltage, current and turnoff characteristics.
7. Allow market place to identify the most viable technology (line commutation versus forced commutation) from the standpoint of inverter cost, delivered energy cost, performance criteria.

8. For line commutated inverters the following should be investigated for improved cost, efficiency and ripple reduction and system protection.
 - A. Three inverter bank versus two bank systems for reduced harmonics.
 - B. Filter optimization for reduced harmonics.
 - C. Larger SCR's (100 mm cells).
 - D. Application of liquid cooling.
 - E. Improvements in capacitors and use of synchronous capacitors.
 - F. Continued development of static DC interruptor with add-on micro-processor control.
9. Larger number of phases in line commutation inverter do not necessarily improve harmonic performance; therefore, development efforts may not provide performance improvements.
10. Review static interrupter performance versus mechanical interrupter in terms of cost, protection and system performance.
11. System electronic controls should be diagnostic in nature and remotely controllable for utility system power management.
12. Factory testing of power conditioners should closely simulate the real installation environment. Procedures and methodology should be investigated.
13. Study efforts should be extended in characterizing of system performance. A generalized system specification should be developed including electrical performance, environmental requirements, reliability, etc.
14. Analysis of power conditioner modularity as related to cost reduction of installation costs.
15. Analytical models are necessary for sources (PV, MHD, fuel cell, battery, etc.).
16. More inverter units needed to be built to identify cost, reliability and performance issues.

CONCLUSION

The overall conclusion of this workshop was that a great deal needs to be done in the areas of power conditioner technology development, performance specifications and standards, harmonic injection and modeling of utility systems in order to more adequately predict operational performance. It is also recommended that additional funding be supplied to initiate power conditioner production in order to identify the system interactive problems and sensible cost goals. Production expertise is necessary to provide a viable system and product.

MEMBERS OF THE POWER CONDITIONING FOR LARGE
SYSTEMS INTEGRATED WITHIN A UTILITY GRID
WORKSHOP GROUP

The Power Conditioning for Large Systems Within a Utility Grid Group consisted of the following persons reflecting a cross-section of industry, universities and government experience.

R. Anderson	Standard Oil of Calif.
D. Englebrecht	Texas Power & Light
R. Ferraro (Panel Speaker)	EPRI
R. Fling	Aerospace Corp.
E. Fuchs	University of Colorado
K. Harner	Hamilton Standard
S. Krauthamer (Panel Chairman)	JPL
B. Lindquist	Chevron Research
A. Maltz	PSE&G
W. Miller	Martin Marietta Aerospace Corp.
R. Pohl (Panel Speaker)	General Electric Co.
J. Prohaska	Alcoa
T. Prouty (Panel Speaker)	Garrett AiResearch
F. Robinson	Garrett AiResearch
D. Roesler	DOE, EES
G. Schmidt	AEG - Telefunken
J. Vivirito (Panel Speaker)	UTC Power Systems Division
J. Walter	Sandia Laboratories
A. Wellford (Panel Speaker)	Exide Power
P. Wood (Panel Speaker)	Westinghouse

Working Group B

POWER CONDITIONING FOR SMALL DISPERSED
SYSTEMS INTEGRATED WITHIN A UTILITY GRID

POWER CONDITIONING FOR SMALL, DISPERSED
SYSTEMS INTEGRATED WITHIN A UTILITY GRID
WORKING GROUP REPORT

DANIEL S. YORKSIE, GROUP LEADER
WESTINGHOUSE AEROSPACE ELECTRICAL DIVISION

INTRODUCTION

Large numbers of small photovoltaic PV systems in residential and intermediate-size applications present new and significant challenges to both the power conditioning system designers and the local operating utility. These challenges can be addressed in an orderly and timely manner and, if so addressed, will facilitate the commercialization of photovoltaic systems.

The purpose of this working group was defined to include the following:

- * Assess current and future technology.
- * Identify operational requirements.
- * Identify mass production and marketing requirements.
- * Identify means to stimulate development.

The scope of the working group included power conditioning systems ranging in size from five to five hundred KVA. This range includes farm, residential, light manufacturing, and commercial applications (i.e. shopping centers, condominiums, etc.). The interface to the utility for these various applications is well defined by existing utility distribution network design and is shown in Figure 1. A more detailed statement of scope was presented (see Figure 2) and accepted by the working group.

The working group was presented with a list of potential topics for discussion (see Figure 3) and a suggested priority for these topics (see Figure 4). It was agreed to discuss these topics in the order of priority suggested but due to time constraints effort would be concentrated on topics one, two and three. In an attempt to stimulate discussion and provide inputs for working group consideration limited background information on interconnect policies, warranties and regulatory policies was presented. This information is contained in Appendix I to this working group report.

The working group then proceeded to address these topics and to formulate a set of recommendations. Overall group effectiveness was enhanced by the diversity of viewpoints presented including government, private laboratories, utilities, universities and industry. A detailed listing of participants is included in Figure 5.

The following sections present a summary of working group discussions on each of the three groups of topics followed by a summary of overall recommendations and conclusions.

GROUP I TOPICS - POWER QUALITY:

Power Quality includes power factor presented to the utility, current and voltage harmonics and radiated or conducted EMI. Historically utilities have relied on Telephone Interference Factor (TIF) rating to control the quality of power generated by rotating apparatus. These requirements are spelled out in ANSI C50.13 - 1977. Recognizing the needs for more specific guidelines for solid state apparatus the Static Power Converter Committee of the Industry Applications Society of the IEEE has published a preliminary guide for certain types of equipment entitled "IEEE Guide For Harmonic Control And Reactive Compensation of Static Power Converters". Some utilities are becoming increasingly concerned about the effect on power quality of various types of connected apparatus. Large numbers of photovoltaic systems could have a deleterious effect on power quality if guidelines for the power conditioner designers are not established in a timely manner. Typically today some utilities have limits on power factor in the range of 0.9 lead/lag. Standards have not been set for current or voltage harmonics but typical values of 10% for current and 5% for voltage are being considered. Obviously with few such systems very loose requirements can be tolerated but as the numbers of such systems increases tighter limits will be imposed. The working group agreed that PV systems should not be made to meet more severe requirements than what is being imposed on other apparatus. Large numbers of small dispersed systems may also create other problems including:

- * Distribution network resonances.
- * Distribution network stability.
- * TV Interferences.
- * AM/FM radio interference.
- * Radiated EMI.

It was pointed out that NASA Lewis Research Center has obtained limited data from a single 8 KW PV installation including a line commutated inverter. Although no TV or FM radio interferences was detected, buzzing in the AM radio band was encountered. Another area of concern was the possible effect of poor power quality on digital (computer) installations although no specific examples were cited. The working group generally agreed that the problem will get worse in time if not addressed. Performance criteria needs to be established to guide manufacturers of power conditioning equipment and also DOE in sponsoring development work in this area.

POWER FLOW INTO THE UTILITY:

Credit for power flow into the utility in PV sites without energy storage can be a significant factor in overall site economics. Only a few utilities are presently addressing this situation and no firm policies and rate structures have been established. In small PV installations with energy storage (i.e. batteries) this factor will probably not be significant. The consensus of the working group was that the two parallel non-reversing watt-hour meter arrangement will become standard. Since the cost of electricity basically includes both a demand charge and an energy charge a possible reasonable and equitable rate structure would consist of the utility selling power at a composite rate reflecting both demand and energy charges and crediting the customer at the energy charge only for power fed back to the utility.

Concern was expressed about potential problems due to significant changes or alternation of the traditional demand profile when large penetration of PV systems occurs. This will probably require more sophisticated control schemes by the utility but no unmanagable problems are anticipated.

SAFETY:

The question of safety was explored from several different perspectives. After the initial discussions it became apparent that the question of safety is more complex than it first might appear. Electric utility linemen, even when following operating procedures, may be working on higher voltage lines (i.e. 13.8 KV) which are not absolutely grounded. With several PCU's, irrespective of type (i.e. line or self-commutated), are operational on the low voltage side the potential exists to back feed the H.V. line thus creating a safety hazard. Reliable and positive means must be designed into the PCU to prevent this equipment from energizing a "DEAD" utility line. A possible scheme might include the utility providing a power line carrier signal which all PV power conditioners would monitor. Absence of this signal would result in all PCU's disconnecting from the utility. Safety of the homeowner must also be considered in the design of power conditioning equipment and sufficient protective equipment must be included in the design to eliminate hazardous operation. Certain system configurations may pose special hazards. For instance, with battery installations a dead short within the PCU could result in dangerous conditions. It was agreed that the PCU must be designed to protect itself internally and not to create a hazard at its interfaces. However, other system requirements such as explosive atmosphere are the responsibility of the appropriate subsystem.

NOTE: Several EPRI studies including RP1192 should provide additional information on power quality and network implications.

GROUP 2 TOPICS - OWNERSHIP

Several forms of ownership are possible including private, leasing and utility. Utility representatives expressed the viewpoint that the majority of electric utilities would not be interested in ownership of small residential units especially in view of the fact that such systems would include rooftop arrays permanently attached to the dwelling. However, medium-size installations such as shopping centers or industrial park complexes of a few hundred kilowatts or larger may be of interest to utilities from an ownership consideration. A possible approach for small residential units would be leasing from the utility, however cost-of-money considerations may not favor this approach.

It was generally concluded that residential units will be built into the home by the contractor, possibly with some form of government support or subsidy, and be financed via the typical home mortgage route. Government incentives and support will definitely be required before large numbers of residential applications become a reality.

The working group was also made aware of current legislative action in some states directed at prohibiting electric utilities, oil companies, etc., from becoming significant factors in this new energy market. This further supported the working group conclusion regarding private ownership.

WARRANTIES:

The power conditioning unit is probably the most reliable element in a PV installation. Experience from other applications such as uninterruptible power supplies indicates 17,000 hour MTBF's are achievable for residential size units. Based on operating hours this represents 5 to 7 years for PV systems. Current design life of 10 to 20 years is acceptable.

The working group concluded that a one-year warranty appears reasonable and fair.

SERVICE:

After a general audience discussion of this topic the group concluded that the "IDEAL" form of service will be the small local business trained to service the products from a number of manufacturers similar to the local TV/Radio repair service today.

GROUP 3 TOPICS - ECONOMICS AND STANDARDS

Standards definitely affect product cost. This is true of both product quality standards and product performance standards (i.e. waveform quality). It was pointed out that electric utilities should logically take the lead in setting guidelines and standards but that DOE has a responsibility to insure that reasonable guidelines and standards are formulated to guide manufacturers of power conditioning equipment. These standards should be no more stringent than for other equipment and may in fact evolve from less to more strict as market penetration of PV systems increases.

On the question of economics the working group agreed that present goals are reasonable and achievable. However, current power conditioning development programs are based on refining and applying the technology gained from UPS, military P.S. and industrial solid state drives. The PV marketplace represents orders of magnitude larger quantities and hence opens the door to advanced and innovative design approaches. VLSI technology and custom hybrid power modules coupled with high frequency conversion techniques to minimize the dollar value of mature components (i.e. inductors, capacitors, transformers) should be investigated to determine if such designs will yield further significant cost reductions. Total system cost must be minimized and any subsystem capable of offering further cost reductions must be vigorously pursued.

RECOMMENDATIONS AND CONCLUSIONS

The following list of recommendations and conclusions were arrived at by this working group.

- * Power quality will become of increasing concern to utilities as PV systems increase their market penetration.
- * Electric utilities are just starting to address the problem and there may be variation from location to location.
- * Typical utility interface requirements may include the following limits:

0.9 power factor, lead or lag (watts/volt amperes)

Voltage total harmonic distortion of 5%

Current total harmonic distortion of 10%

- * Dual power meters will probably become standard with utilities selling at a composite demand/energy rate and crediting at the energy rate only.
- * DOE should sponsor a study to determine the impact of multiple dispersed PV systems on the electric utility grid.
- * DOE should use existing and planned PV demonstration sites to take measurements and study the effects of conducted and radiated EMI/RFI generated at both the AC interface (utility) and the DC interface (array). Effects on TV, radio and computers should be determined and guidelines established.
- * Theoretical analyses of the impact of large numbers of dispersed PV systems should be confirmed by appropriately sized field trials. For example, DOE subsidizing the installation of a number of residential PV systems in a typical subdivision or military base would provide such a test bed.
- * A limited number of high risk advanced technology power conditioning development programs should be funded by DOE in support of the overall PV goal to minimize total system cost.

LIST OF PARTICIPANTS

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Figure 5

LIST OF PARTICIPANTS, CON'T.

Frank Goodman

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Figure 5.1

TYPICAL UTILITY DISTRIBUTION

Fig 1

STATEMENT OF SCOPE

- **POWER CONDITIONING**

Electronic apparatus for converting DC Output of PV Array to utility grade AC power.

- **POWER LEVEL**

Typically 5-20KVA 50/60 Hz Single Phase or 20-50KVA Three Phase. Multiple unit clusters less than few hundred KVA.

- **DISPERSED**

Few hundred feet between units to a few miles between units.

- **UTILITY INTEGRATION**

Must be capable of operating tied to a utility line. May also be capable of operating without the utility.

Figure 2

STATEMENT OF SCOPE (continued)

- **TYPE OF USER**

Residential, small manufacturing, farm.

- **TYPE OF LOADS**

Utility type including motors, pumps and machinery.

- **CONFIGURATIONS**

Attended/Unattended automatic with/without energy (battery) storage.

- **LOCATION**

Worldwide developed and developing countries.

POTENTIAL TOPICS FOR WORKSHOP DISCUSSION

- **Power Level**
- **Reliability / Maintainability**
- **Warranty**
- **Service**
- **Power Quality**
- **Safety**
- **Electromagnetic
Interference, Compatibility**
- **Economics**
- **Instrumentation / Gauges**
- **Power Flow Into Utility**
- **Reversal of Watt-Hour Meters**
- **Ownership—Leasing, Private, Utility**
- **Harmonics—Voltage, Current**
- **Acoustic Noise**
- **Testing**
- **Design Life**
- **Environment—Temperature, Humidity**
- **Peak Power Tracking**
- **Packaging—Physical Size,
Volume, Dimension Constraints**

Figure 3

SUGGESTED PRIORITY FOR WORKSHOP TOPICS

PRIORITY 1

- **POWER QUALITY**
 - **Power Factor To Utility**
 - **Current Harmonics**
 - **Voltage Harmonics**
- **SAFETY**
- **POWER FLOW INTO THE UTILITY**
 - **KWH Meter Reversal**

PRIORITY 2

- **RELIABILITY (AVAILABILITY)**
- **MAINTAINABILITY**
- **WARRANTY (DESIGN LIFE)**
- **SERVICE**
- **OWNERSHIP**
 - **Consumer Credit Terms (Private)**
 - **Lease**
 - **Utility Ownership**

SUGGESTED PRIORITY FOR WORKSHOP TOPICS (Continued)

PRIORITY 3

- **ECONOMICS**
- **STANDARDS**
- **PEAK POWER TRACKING**

PRIORITY 4

- **ENVIRONMENT**
- **PACKAGING**

APPENDIX I

BACKGROUND INFORMATION

- **INTERCONNECT POLICIES**
- **WARRANTIES**
- **REGULATORY ACTS**

GEORGIA POWER COMPANY

Statement Of Requirements For Parallel Operation Of Customer Generation

- 1. Prompt removal of infeed whenever a fault occurs. Ownership of protective devices preferably is with G.P.C.**
- 2. All generators greater than 10KVA must be three phase.**
- 3. Additional interconnect equipment cost to be borne by customer.**
- 4. Negative sequence currents may flow in the customer's generator and he must protect for them.**

GEORGIA POWER COMPANY
Statement Of Requirements For
Parallel Operation of Customer
Generation (Continued)

- 5. Normally power transformer isolation is required.**
- 6. Customer will not be permitted to energize a dead G.P.C. Circuit.**
- 7. Revenue metering will include two parallel connected non-reversing watt-hour meters.**
- 8. Interconnection shall not cause any reduction in the quality of service being provided to other customers with no abnormal voltages, frequencies or interruptions being permitted.**

WARRANTIES

From SOLAR AGE (MAY 79)

"A Challenge for Warranties"

W. L. Haworth & J. M. Mattila

- **MANDATED BY GOVERNMENT**
- **EVOLVE FROM MARKETING TOOLS AT THE DISCRETION OF INDUSTRY**
- **WARRANTY LIMITS**
 - **Defects in material and workmanship for components drive system.**
 - **Dismantle, shipping, re-install costs.**
 - **Parts**
 - **Labor**
- **DURATION OF WARRANTY**
- **TRANSFERABILITY OF WARRANTY**
- **MAINTENANCE CONTRACTS**
- **UNIFORMITY & SIMPLIFICATION**

PURPA

The Public Regulatory Police Act of 1978 requires that all state regulatory agencies conduct an extensive review of utility rate structure.

- **Cost of Service**
- **Time of Day Rates**
- **Interruptible rates**
- **Declining Block Rates**
- **Load Management Techniques**

State agencies are not required to adopt any changes but if they do not accept the federal standards, they must explain their reasons to the public.

Working Group C

POWER CONDITIONING FOR STAND-ALONE
AND DC APPLICATIONS

10 May 1979
Group C
1:30-4:30 PM

INTRODUCTION

The purpose of this workshop was to assess power conditioning for use in stand-alone and DC systems. Participants included representatives from PV array, power conditioning and battery manufacturers; military application representatives, and private contractors (including one from the recreational field--Disneyland). There were no participants present from DOE, the educational field or public utilities, possible because other meetings of greater interest to these groups were going on concurrently.

Stand-Alone Systems (AC)

Military representatives were interested in systems of up to a few hundred kilowatts. For them, procurement of power conditioning units was not a problem, probably because military construction is so expensive to start with that the increment of cost for PV compatibility is relatively small. The problem of obtaining equipment for operation at arctic temperatures was mentioned. There was a short discussion on AC motor starting problems, especially in air-conditioning compressors. A consensus was expressed for a standard format for inverter overload specifications.

Low Power DC Systems

The remaining discussion centered on relatively small remote DC systems. Discussed specifically were:

- Array/battery sizing
- Battery characterization and management
- Lightning protection
- DC-DC converters
- Maximum power point trackers

Since DC systems tend to be used for low power remote applications, such systems are generally so far ranging and diverse in their make up as to make it virtually impossible to discuss in this context general power conditioning applications (except that most have in common batteries and regulators). Battery charge regulation evoked much discussion even though it is not power conditioning per se. The group would like to see handbook information on:

- Battery sizing, such as choice of daily deep cycle vs. long-term averaging.
- Battery management and its effects on lifetime and cost.
- Battery state of charge.
- Instrumentation, such as in situ removable specific gravity sensors.

Battery charge regulation is done almost universally with shunt dissipative regulators. Two manufacturers present built units of their own design; both had decided to build because suitable units were not available. One builds 50 units per week to satisfy his own needs and has no expansion plans. His product has a high labor cost but he believes an increased automation investment is not presently justifiable. The other manufacturer builds up to 300 units per run, at 20 to 360 W rating, which are supplied as OEM units.

The discussion then moved on to non-dissipative "switching" type regulators. The effect of switching rate upon battery lifetime was discussed. The battery manufacturers stated that slow rates would chemically "work" the plates and shorten life. They recommended switching frequencies above 100 Hz. Above this frequency the electrolyte/plate interface is essentially a capacitor and the plates are not chemically "worked". This raised the question of possible electromagnetic interference by radiation from the PV array.

Lightning protection was a topic of general interest. A direct strike was presumed to be catastrophic but protection from induced surges from nearby strikes was also of concern. Again, a desire was expressed for a handbook

of standardized information on economical lightning protection for small systems, with specific details on:

- o Overvoltage clamping and devices
- o Transmission line effects and reflections of surges
- o Disconnect devices such as fuzes and possible self-restoring devices.

A short discussion followed on availability of low power DC-DC converters. Apparently, there are few suppliers of converters, prices are high, and units are of better quality than necessary. A desire was expressed for a line of "up-converters" which would allow the use of fewer solar cells and battery cells in series. Such a system would be of low voltage, 4 or 6 volts, yet run loads of 12 or 24 volts.

Conclusions and Recommendations

Topics requiring further consideration are:

- Standard inverter overload specification
- Handbook: Array-battery sizing
- Battery characterization
- Handbook: Lightning protection for small PV systems
- Battery state of charge sensing
- Effect of frequency choice of non-dissipative regulators on battery life.