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EVALUATION OF RECENT RESIDENTIAL INVERTERS

June 1982

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ABSTRACT

Seven residential utility-interactive inverters for photovoltaic power systems have been evaluated at MIT Lincoln Laboratory and at the Northeast Residential Experiment Station (NE RES). Two, a Windworks "Gemini" and an Abacus "Sunverter," have been reported on previously. Reviewed here are five other inverters: Windworks Gemini 8-kW (dc) model with an ac filter to improve the output current waveform and power factor; Acheval Wind Electronics 10-kW (ac) model, Helionetics 6-kW (dc) model; and American Power Conversion 2-kW and 4-kW (ac) models. Input and output power, power factor, current waveform distortion, audio noise and radio frequency interference measurements were made at the NE RES and the results are presented.

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Seven residential inverters have been evaluated at MIT Lincoln Laboratory and at the Northeast Residential Experiment Station (NE RES). Two, a Windworks "Gemini" and an Abacus "Sunverter," have been reported on previously by Landsman[1,2] and five are reviewed here. They are: (1) Windworks Gemini 8-kW dc input model with an ac filter to improve the output current waveform and power factor, (2) Acheval Wind Electronics 10-kW ac output model, (3) Helionetics 6-kW dc input model, and (4,5) American Power Conversion 2-kW and 4-kW ac output models. The Windworks and Acheval units are installed in the MIT Lincoln Laboratory prototype at the NE RES for evaluation. The Acheval operates continuously and the Windworks is tested on occasion while it awaits a "night switch" modification, after which it will be moved to the TriSolarCorp prototype for further evaluation. The Helionetics unit is installed in the Solarex prototype, and the American Power Conversion 4-kW unit is installed in the Westinghouse prototype; the 2-kW unit was in the Westinghouse prototype for six weeks.

DC input and ac output power measurements were made using the NE RES data system. Power factor was calculated from the current phase angle measured on the calibrated oscilloscope, except for the Windworks inverter with the ac filter and the Acheval inverter. In these cases, the VARs were measured with the mechanical kVARh meter and the power factor calculated. Current waveform distortion was measured using a Hewlett Packard 3581A wave analyzer.

Audio noise level was measured with a General Radio standard sound level meter, three feet from the inverter, with a microphone at 90 degrees to a line toward the inverter, using the dBA (weighted) scale. A "quiet" residence has a noise level in the range of 25-35 dBA. Noise sources greater than 40 dBA are easily noticeable and may be objectionable unless located in the basement, garage, closet or are sound-insulated. Noise sources greater than 60 dBA require special mounting isolators and sound insulation to reduce noise to an acceptable level for a residence.

Radio frequency interference was measured with a receiver at 10 ft. from the inverter. Interference was detected only on the AM band, none on the FM band. Noise levels equal to strong stations were rated "high", to weak stations "moderate" and, if noticeable only between stations, "low."

2.0 WINDWORKS INVERTER WITH AC FILTER

Windworks, Inc., under contract to MIT Lincoln Laboratory, undertook a study to design and build an ac filter for their 8-kW dc input residential inverter. Specifications called for an efficiency of 90% or better weighted over the operating levels, total current harmonic distortion of 5% or less with no one component greater than 3%, and a power factor of 0.85 or better at full power. Analog computer simulations were undertaken at the MIT Parity Simulator[3] facility in Cambridge. The selected design consisted of three series-tuned filter sections in parallel, predicted to meet the contract requirements.

The basic "Gemini" inverter is a commercial wind power system component modified for solar PV use. The modified inverter with the ac filter is shown in Fig. 1 and the measured characteristics are given in Table I.

TABLE I

WINDWORKS INVERTER WITH AC FILTER

DC input:		8 kW (rated)
AC output:		7.4 kW
Efficiency:		92% at 6.1 kW (ac)
Power factor:		.99 (inductive) at 6.1 kW (ac)
Total current distortion:		4.9% of fundamental at 6.1 kW (ac)
Night ac power (without night switch):		400 W
Night VARs (without night switch):		8000 VARs (capacitive)
	Size	Weight
Inverter	30"H 24"W 12"D	230 lbs
AC Filter	30"H 24"W 12"D	460 lbs
Transformer	12"H 14"W 9"D	200 lbs
	(10.9 cu ft)	890 lbs

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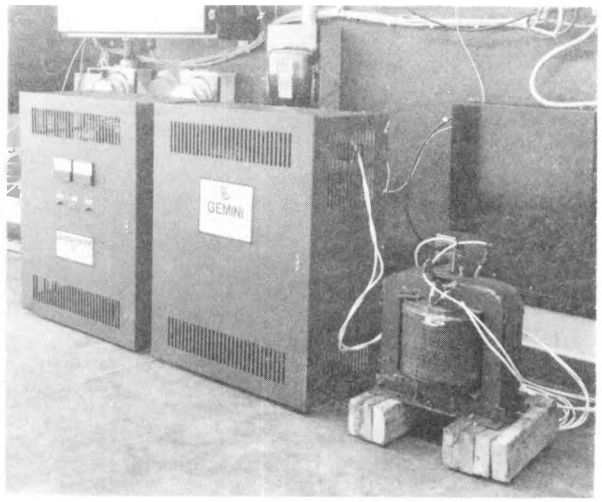

(a). Outside.

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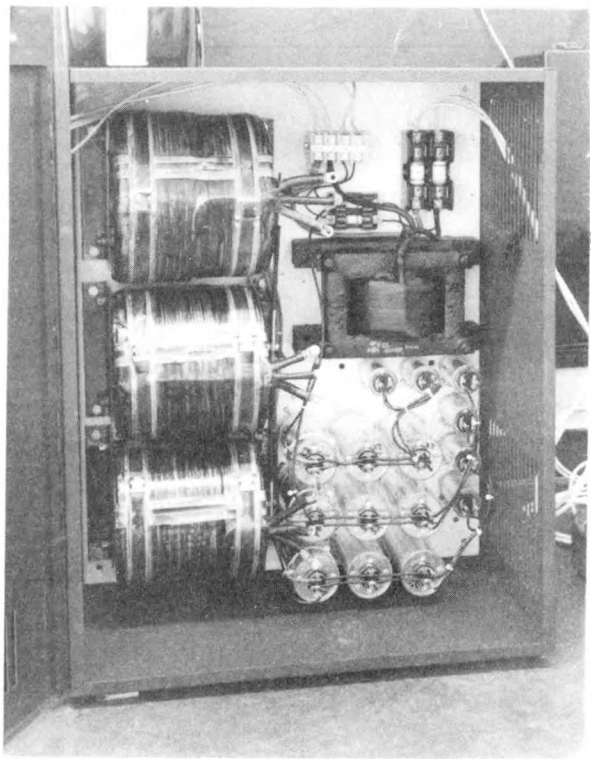

(b). AC filter.

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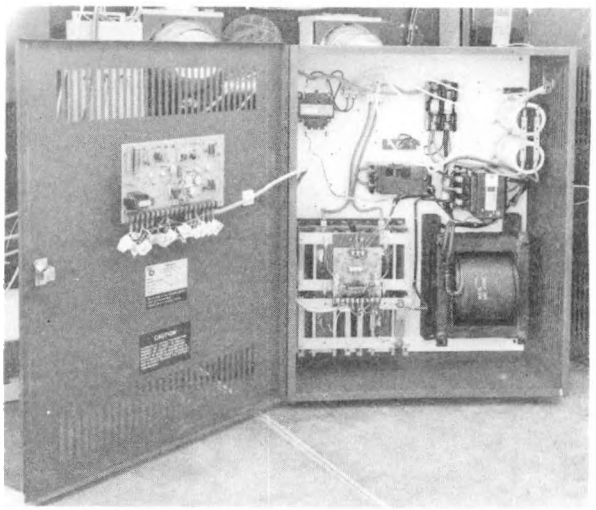

(c). Inverter and dc filter.

Figure 1. Windworks inverter with ac filter.

The prototype unit is assembled in two oversized cabinets with an external transformer. One cabinet houses the inverter and dc filter; the other houses the ac filter. The unit is a line-commutated, SCR bridge design with a constant voltage control mode. An isolation transformer is included. Because of the high ac current and VARs with no dc input, a "night switch" is recommended for continuous operation; a modification to the unit has been requested of Windworks. Installation is scheduled for late June 1982.

Figure 2 shows curves of power factor, ac current and VARs for various ac output powers, and Table II gives the measured and predicted data. Figure 3 shows the reference voltage waveform with current waveforms for various output powers.

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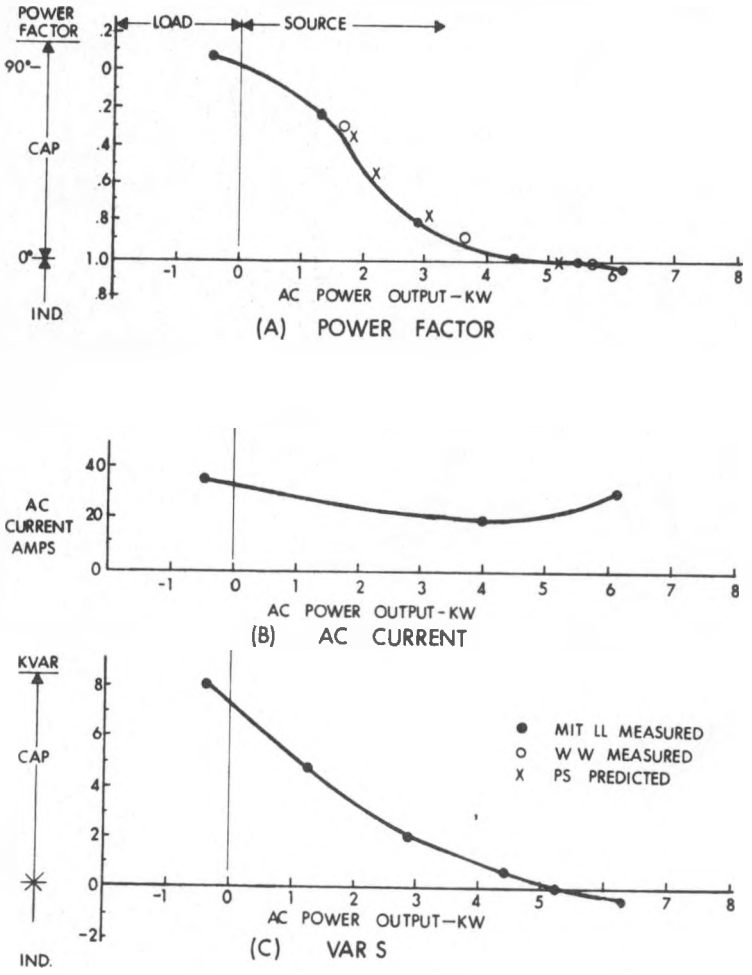

Figure 2. Performance of Windworks inverter with ac filter.

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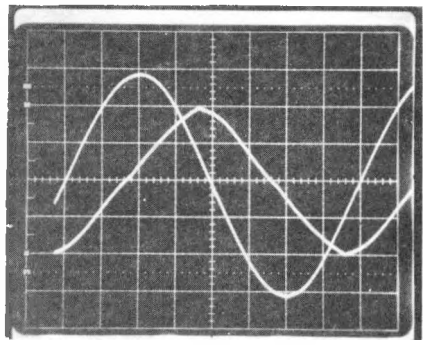
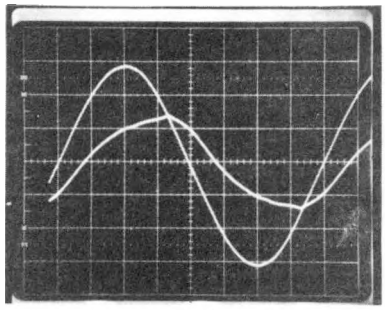


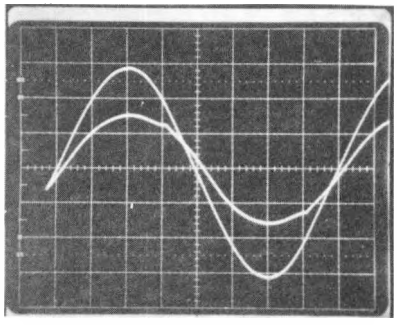
(a)
1.31 kW (ac);
.26 power factor (cap.)

C74-2012



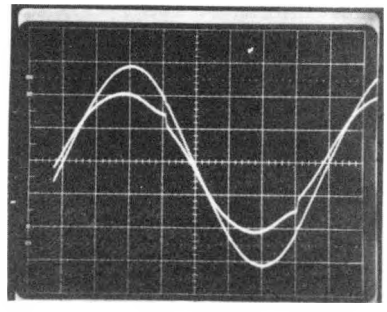
(b)
3.03 kW (ac);
.81 power factor (cap.)

C74-2011



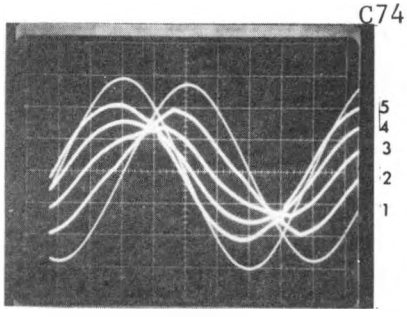
(c)
4.57 kW (ac);
.99 power factor (cap.)

C74-2013



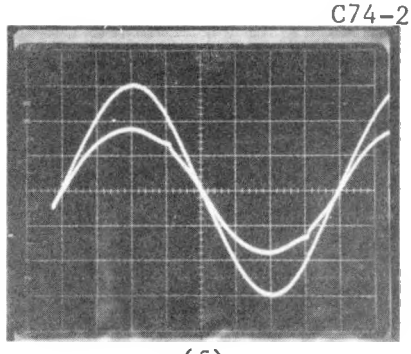
(d)
6.05 kW (ac);
.99 power factor (ind.)

C74-2014



(e)

C74-2015



(f)
5.29 kW (ac);
1.0 power factor (0 VARs)

	AC Power Output	Power Factor	kVARs
1.	-.4 kW (load)	.05 (cap.)	8.0
2.	1.23	.26 (cap.)	4.6
3.	2.92	.81 (cap.)	2.1
4.	4.51	.99 (cap.)	.7
5.	6.10	.99 (ind.)	.7

Figure 3. Inverter waveforms.

TABLE II

INVERTER PERFORMANCE

Source	Output (ac kW)	Power factor	Angle Deg.	Tan^{-1}	kVARs
Lincoln	-.4	.05 (C)	87	20	8.0
Laboratory	1.23	.26 (C)	75	3.73	4.6
(measured)	2.92	.81 (C)	36	.73	2.1
	4.51	.99 (C)	9	.158	.7
	5.29	1.0	0	0	0
	6.10	.99 (I)	6	.108	.7
Windworks	1.7	.37			
(measured)	3.7	.91			
	5.6	1.0			
	7.5	.96			
Parity Simulator	1.8	.4			
(predicted)	2.2	.6			
	3.1	.8			
	5.1	1.0			

Total harmonic distortion of the current waveform was measured as 4.9% of the fundamental at the 6.1-kW ac output level with major components as 4.5% (3rd), 1.1% (7th) and 0.9% (9th).

The inverter design and model met the specifications for efficiency, power factor and output current waveform total harmonic distortion. At the 6.1-kW (ac) level, the 3rd harmonic level exceeded the specification. Windworks has measured the 3rd harmonic as 4% at full power, closer to the specification. The night switch is required for continuous operation, and this modification will be evaluated later. However, at output power levels below 2 kW, the power factor will be below 0.6. It remains to be seen whether this feature will be acceptable to utilities for general service, especially at high penetration levels in the future.

Audio noise level is unacceptably high for uninsulated residential installations. Radio frequency interference to the AM band is high and must be reduced before widespread general use.

Reliability of the basic inverter has been high, but no information is available on performance with this modification.

The manufacturer has predicted the high-quantity production cost for the filter at $1200. This figure added to the basic inverter price of $2800 brings the cost to $4000, or $.54/W ac power output.

The night switch modification has recently been made to the inverter by the manufacturer and, following some readjustments, satisfactory summer operation resulted. 460 watts of array dc power are required to just overcome the ac load imposed by the inverter and filter. The inverter turns on when the array open-circuit voltage reaches a preset value such that the array can just furnish adequate power for delivery of ac power to the utility, and it turns off when the array current drops below a preset value when the array no longer can furnish adequate power.

Unfortunately, the open-circuit voltage is insolation- and cell temperature-dependent so one setting is not valid year round. Higher values are required for winter than for summer. If the setting is too low, the inverter will cycle on and off until the voltage and current criteria are met, and if the setting is too high, available power will be lost. Further refinement of the night switch controller operation is recommended.

3.0 ACHEVAL INVERTER

The Acheval Wind Electronics Source Independent Line-Commutated Inverter ("SILCI") is a commercial wind power system component modified for solar PV use. The inverter is shown in Fig. 4 and the measured characteristics are given in Table III. The unit is a line-commutated SCR bridge design with a constant voltage control mode and has no isolation transformer or night switch. The tested model is rated at 10-kW ac output and the manufacturer claims it will handle an overload of 137% ac power output for short periods, a useful feature for wind gusts or extraordinary sunshine conditions.

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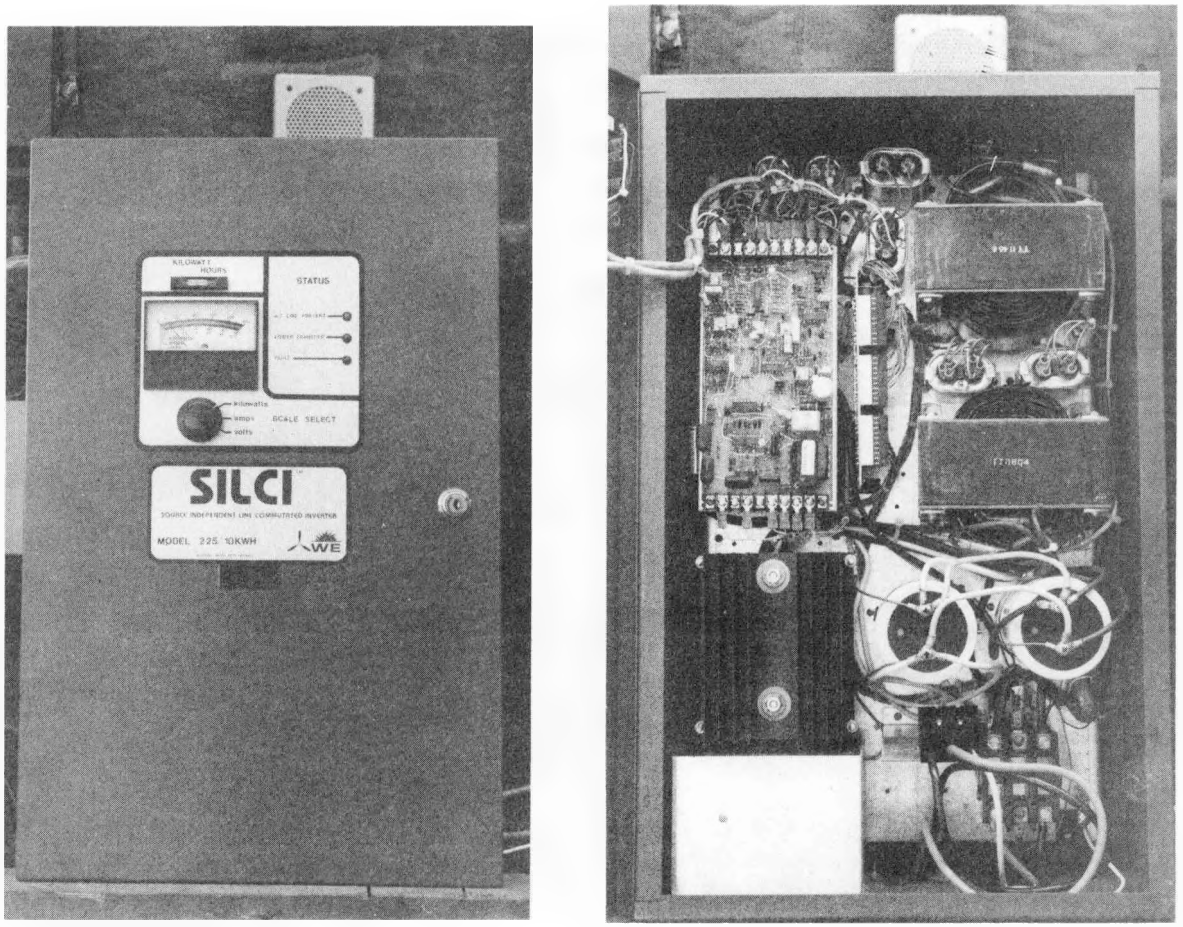

(a) Outside. (b) Inside.

Figure 4. Acheval inverter.

TABLE III

ACHEVAL INVERTER

DC input:	10.9 kW
AC output:	10.0 kW (rated)
Efficiency:	92% at 7.0 kW (ac)
Power factor:	.69 (inductive) at 7.0 kW (ac)
Total current distortion:	65% of fundamental at 7.0 kW (ac)
Night ac power:	48 W
Night VARs:	254 VARs (capacitive)
DC power for threshold ac power delivered:	60 W
Size:	24" H, 15" W, 8 " D (1.7 cu. ft.)
Weight:	95 lbs.

Figure 5 shows the reference voltage waveform with current waveforms for various output power levels.

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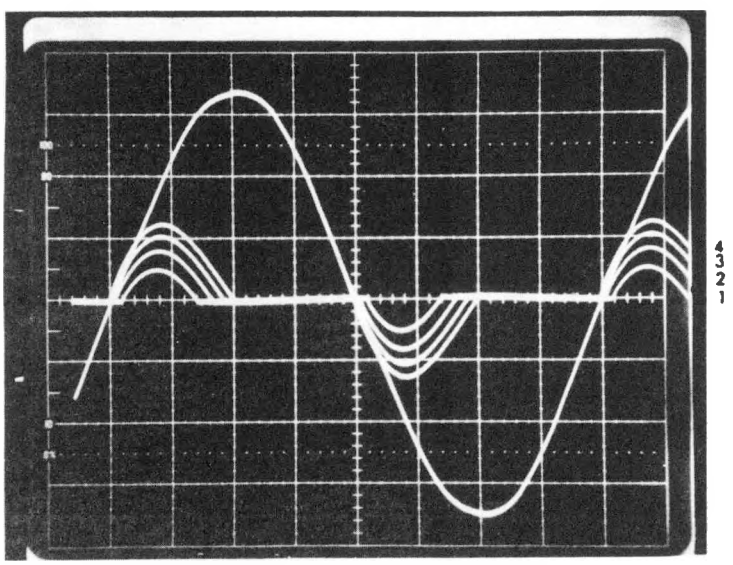

Figure 5. Acheval inverter waveforms.

1. 1.71 kW
2. 3.62 kW
3. 5.57 kW
4. 7.49 kW

Total harmonic distortion of the current waveform was measured as 65% of the fundamental at 7 kW (ac) with major components as 63% (3rd), 13% (5th), 8.9% (7th), 3.2% (9th), 3.5% (11th) and 1.6% (13th).

The current waveform and power factor of this inverter probably are unacceptable to utilities for general service, especially at high penetration levels in the future.

Use of this inverter without an isolation transformer requires that the array not be grounded; a separate isolation transformer may be added if needed.

Audio noise level is high (60 dBA) and will require insulation except in remote locations. Radio frequency interference to the AM band is moderate and must be reduced before widespread general use.

The inverter has been in continuous operation for about three months and, following an early modification, has had no failures.

The inverter cost $2300 with the PV modification or $.23/W ac power output.

4.0 HELIONETICS INVERTER

The Helionetics, Inc., Delta Electronic Control Division (DECC) inverter is a new residential model designed by the makers of large, industrial, 3-phase inverters, including some for PV applications. The inverter is shown in Fig. 6 and the measured characteristics are given in Table IV. The unit is a self-commutated, transistor bridge design with a maximum-power-point tracker control mode. It includes an isolation transformer and has no night switch.

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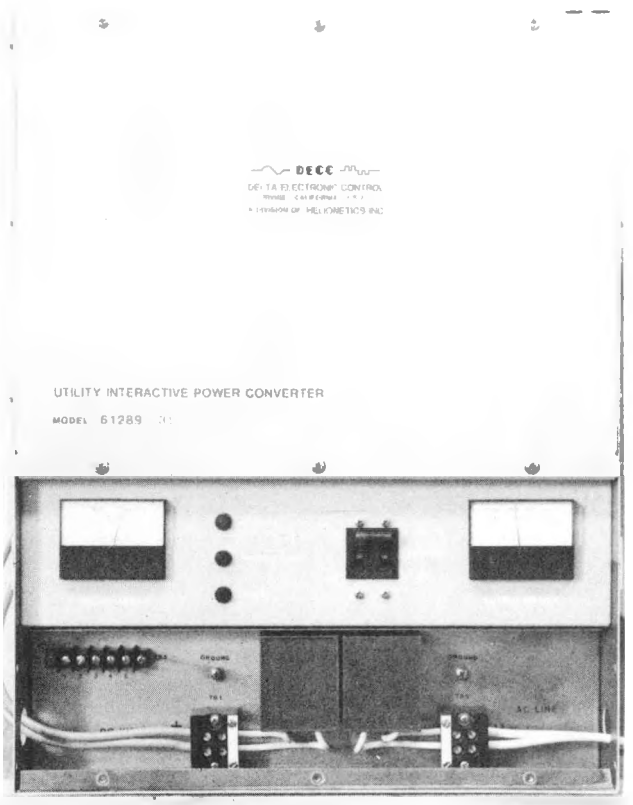

Figure 6. Helionetics inverter.

Table IV

HELIONETICS INVERTER

DC input:	6.0 kW (rated)
AC output:	5.5 kW
Efficiency:	91% at 4.1 kW (ac)
Power factor:	.99 (capacitive) at 4.1 kW (ac)
Total current distortion:	4.4% at 4.1 kW (ac)
Night ac power:	17 W
Night VARs:	0
DC power for threshold ac power delivered:	100 W
Size:	23" H, 17" W, 21" D (4.8 cu. ft.)
Weight:	300 lbs.

Figure 7 shows the reference voltage waveform with current waveform for the 4.1-kW (ac) power level.

C74-2016

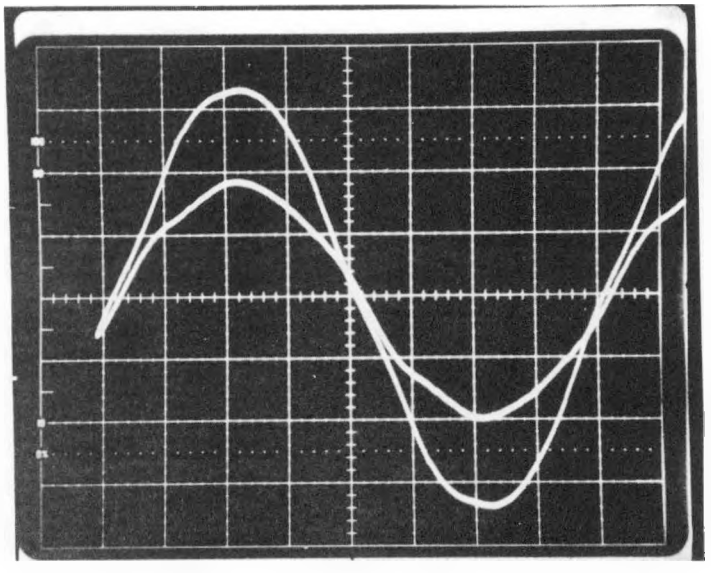

Figure 7. Helionetics inverter waveforms.

Total harmonic distortion of the current waveform was measured as 4.4% of the fundamental at 4.1 kW (ac) with major components as 2.2% (3rd), 3.5% (5th) and 1.3% (7th). Power factor is very close to 1.0 at all power levels.

Audio noise level is moderate (53 dBA) and probably acceptable for residential use. However, an annoying squeal near 16 kHz is noticeable to bystanders but will probably not be objectionable if the unit is remotely located. Radio frequency interference to the AM band is moderate and must be reduced before widespread general use.

The inverter has been in continuous operation for about one month and an identical unit at the Southwest Residential Experiment Station has been operating for several months, both without failure.

The inverter cost $9500, or $1.73/W in small-production quantities, but the manufacturer predicts a cost saving of about one-third for quantities in the hundreds. Looking further into the future, the manufacturer predicts the cost of a mass-produced unit, based on the present design but with different packaging, may be one-seventh of the present cost.

This unit is a promising inverter for residential use with good current waveform and power factor if production cost predictions can be met. Maximum-power-point tracking performance measurements are underway.

5.0 AMERICAN POWER CONVERSION CORPORATION INVERTERS

5.1 2-kW (ac) Model

The American Power Conversion Corporation "Sunsine" inverter, shown in Fig. 8, is a new residential model design and measured characteristics are given in Table V. The unit is a waveshaped, transistor bridge design with a maximum-power-point tracker control mode and includes an isolation transformer and night switch. Figure 9 shows the reference voltage waveform with current waveform for the 1.5 kW (ac) level.

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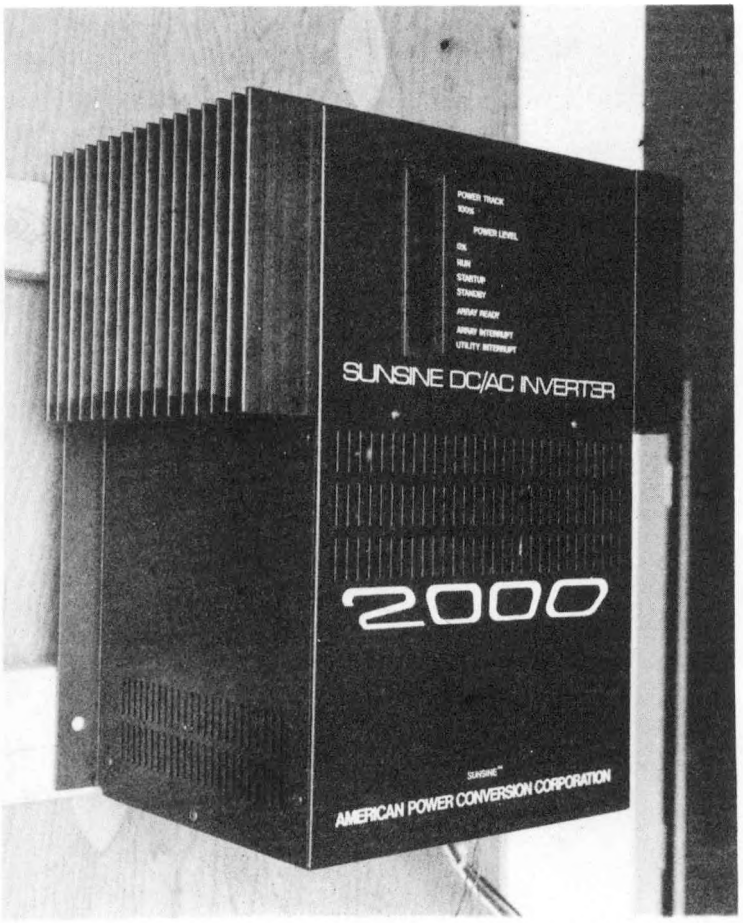

Figure 8. American Power Conversion 2-kW inverter.

TABLE V

AMERICAN POWER CONVERSION CORPORATION INVERTER
(2-kW (ac) Model

DC input:	2.2 kW
AC output:	2.0 kW (rated)
Efficiency:	90% at 1.4 kW (ac)
Power factor:	.99 (inductive) at 1.5 kW (ac)
Total current distortion:	1.1% at 1.5 kW (ac)
Night ac power:	4 W
Night VARs:	0
Size:	17" H, 13" W, 10" D (1.3 cu. ft.)
Weight:	97 lbs.

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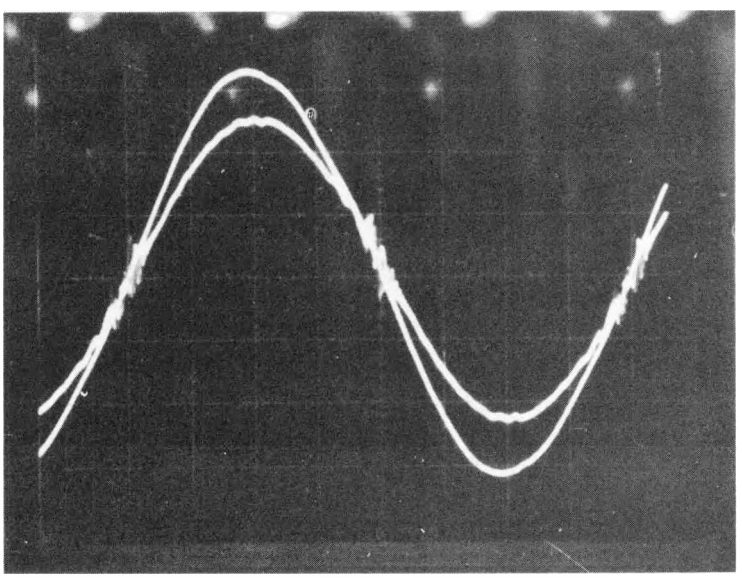

Figure 9. American Power Conversion 2-kW inverter waveforms.

Total harmonic distortion for the current waveform was measured as 1.1% of the fundamental at 1.5 kW (ac) with major components as .4% (2nd), .9% (3rd), .3% (5th, 7th, 9th and 11th each). Power factor is very close to 1.0 at all power levels.

Audio noise level is low and acceptable for residential use and no radio frequency interference to the AM band was observed.

The inverter required some modifications during an initial shakedown period but has been operating continuously for a month and a half without failure.

The inverter cost $3980 or $1.99/W ac power output.

This unit is a promising inverter for residential use with good current waveform and power factor if production cost predictions can be met. (See note on predicted costs for the 4-kW model in the next section.) Maximum-power-point tracking performance measurements are under way.

5.2 4-kW (ac) Model

The American Power Conversion Corporation 4-kW (ac) "Sunsine" inverter, shown in Fig. 10, is similar to the 2-kW (ac) model, and has two paralleled 2-kW output modules; measured characteristics are given in Table VI. Figure 11 shows the reference voltage waveform with current waveform for the 2.9 kW (ac) level. Total harmonic distortion for the current waveform was measured as 1.5% of the fundamental at 2.9 kW (ac) with major components as .5% (2nd), .9% (3rd), .6% (7th) and all the rest below .5%.

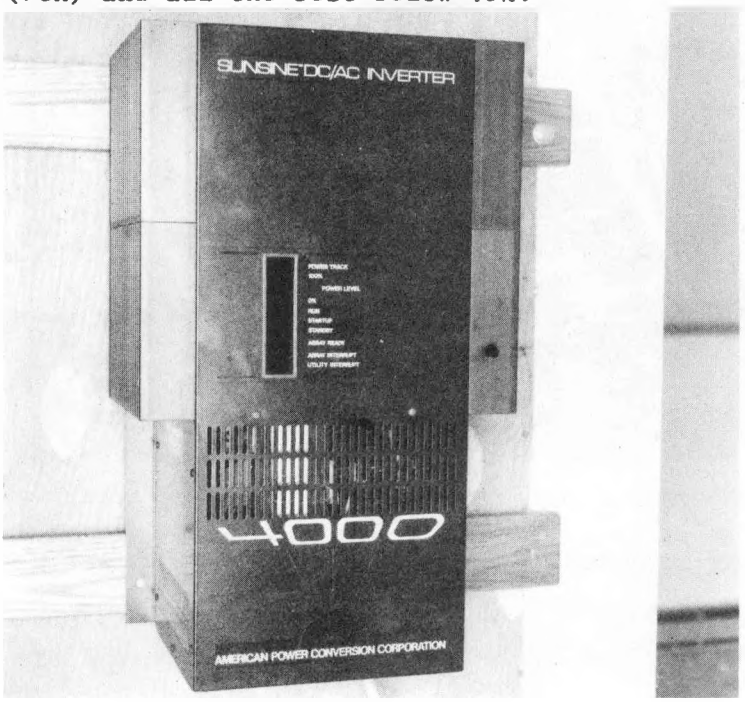

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Figure 10. American Power Conversion 4-kW inverter.

TABLE VI

AMERICAN POWER CONVERSION CORPORATION INVERTER
4-kW (ac) Model

DC input:	4.3 kW
AC output:	4.0 kW (rated)
Efficiency:	92% at 2.9 kW (ac)
Power factor:	1.0 at 2.9 kW (ac)
Total current distortion:	1.5% at 2.9 kW (ac)
Night ac power:	3 W
Night VARs:	0
DC power for threshold ac power delivered:	40 W
Size:	24"H, 13" W, 10" D (1.8 cu. ft.)
Weight:	118 lbs.

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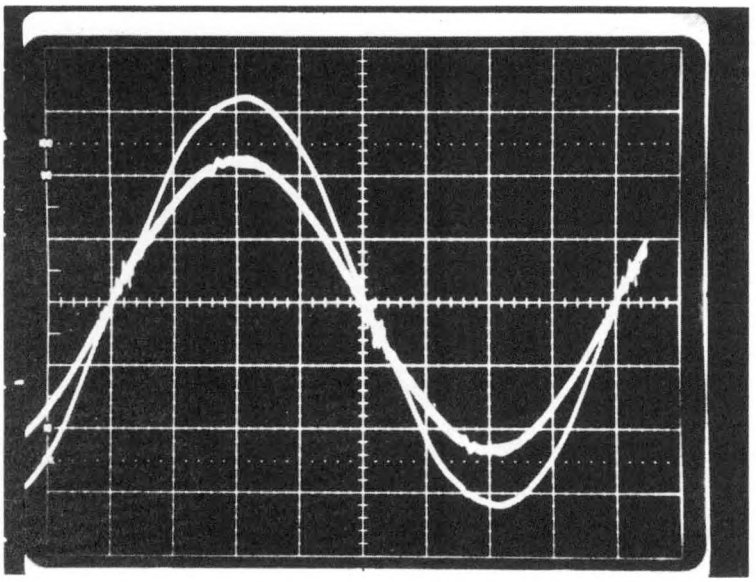

Figure 11. American Power Conversion 4-kW inverter waveforms.

Power factor is very close to 1.0 at all power levels.

Audio noise (50 dBA) was higher than the 2-kW model but probably acceptable for residential use if remotely located. Radio frequency interference to the AM band is moderate and must be reduced before widespread general use.

The inverter has been in continuous operation for several weeks without failure.

The inverter cost $4985, or $1.25/W ac power output. The manufacturer predicts a cost of $.49/W (ac) for quantities of 1000 per year and even lower for larger quantities.

This unit is a promising inverter for residential use with good current waveform and power factor if production cost predictions can be met. Maximum-power-point tracking performance measurements are under way.

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