March 1999 • NREL/SR-520-26085

Subcontractor Report

SunSine™300: Manufacture of an AC Photovoltaic Module

Final Report, Phases I & II
25 July 1995 — 30 June 1998

G. Kern
Ascension Technology, Inc.
Lincoln, Massachusetts

National Renewable Energy Laboratory

1617 Cole Boulevard
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SunSine™300 Photographs

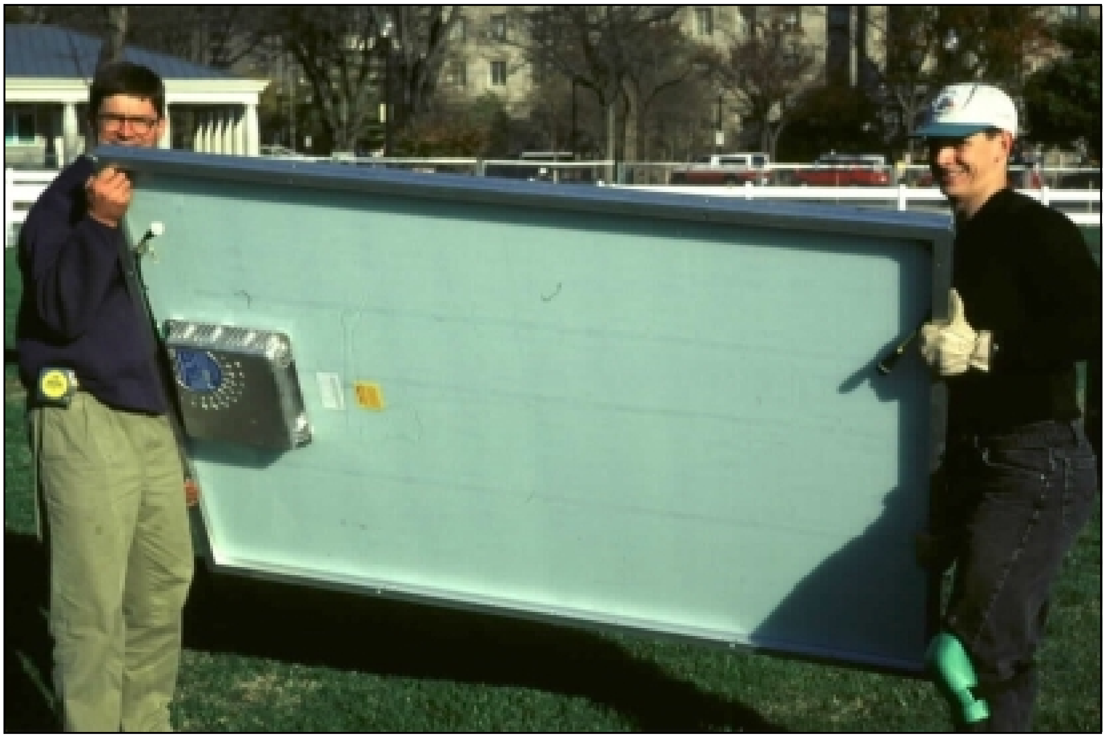

Figure 1 SunSine™300 Rear View

Figure 2 SunSine™300 Front View

Glossary of Terms

EMC. Electromagnetic compatibility or compliance, relates to the electrically conducted or radiated emissions from a unit typically in the range of 150 kHz to 1 GHz in frequency. Most countries have standards which limit the amount of energy products can emit in this frequency range.

EMI. Electromagnetic interference.

FCC. Federal Communications Commission. The authority in the United States which determines allowable levels of EMI and sets EMC standards.

Four-Quadrant Converter. A power converter which can deliver both real and reactive ac power. Instantaneous power flow can be bi-directional.

HALT. Highly accelerated life testing. A test procedure used to quickly uncover potential process or design defects in a product. The test procedure includes thermal and vibrational stresses following a specific test regimen.

HAST. Highly accelerated stress testing. A test procedure used to quickly uncover potential process or design defects in a product. The test procedure includes thermal, humidity and atmospheric pressure stresses following a specific test regimen.

MOSFET. Metal oxide semiconductor field effect transistor, a common power electronics component used in the design of switch mode power converters.

MTBF. Mean time between failure.

RH. Relative humidity.

THD. Total harmonic distortion, a measure of the degree to which a signal deviates from an ideal sine wave in shape.

Two-Quadrant Converter. A power converter which can only deliver real ac power. Instantaneous power flow can only be uni-directional.

Executive Summary

The purpose of this PVMaT 4A1 project was to establish manufacturing capability and enter commercial production with the SunSine™300 AC Module. This goal was achieved when production began in September 1997, first units were shipped in December 1997, and the pilot production of 109 units was completed in the spring of 1998. As of the completion of this PVMaT 4A1 project, production capacity is 2500 units per year, which represents 627.5 kW AC @ STC.

In order to have a commercially viable product, a number of technical goals had to be achieved. UL Listing was achieved in October, 1997. FCC EMC requirements were met in July 1997. Highly Accelerated Lifetime Tests (HALT) and Highly Accelerated Stress Tests (HAST) were conducted in the spring of 1997 and helped to identify potential failure modes, which were later corrected, before the unit when into production.

This report provides the background of the development process which led to a commercial version of the SunSine™300. This report describes the SunSine™300 product, including theory of operation. This report also provides a summary of all the significant test methods which were applied to prototypes of the product with a summary of test results. This report ends with a summary of the Production Process and a list of project sponsors who received units for evaluation.

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History of the SunSine™300 Development

Initial Investigations sponsored by New England Electric System

Ascension Technology, Inc. began development of an AC PV module in 1991 with a grant from the New England Electric System. This early work was the first serious attempt by the company at power conversion electronics development. A hardware prototype of part of an AC Module inverter was built and tested. Lessons were learned from this early project and helped to formulate later developments of the AC Module.

Prototype Development sponsored by Sandia National Laboratories

Sandia National Laboratories sponsored the next step in the development of the AC Module in 1994. A review of power topologies was conducted and balanced with the technical tradeoffs of the various approaches. An approach using a 60 Hz isolation transformer was chosen for three reasons; first, the approach would be simple so the development risks would be low, second, the isolation transformer was percieved to have benefits which customers would be wiling to pay for, and third, the costs compared to other approaches looked to be worth the higher quality of the end product.

A working prototype, a second generation AC PV Module was built, tested and delivered to Sandia for field testing. Lessons were learned during this development phase which were then applied to the next phase.

PVMaT 4A1 (This Project)

On July 26th, 1995, Ascension Technology was awarded a subcontract with NREL under the DOE PVMaT project to commercialize and manufacture the SunSine™300 AC PV Module. This is the project reported on in this document. Under this project a third and fourth generation AC PV Module design was created. The fourth generation design was put into production beginning September 1997, with the first product shipments in December 1997.

Project Statement of Work Summary

Task 1 – Utility Design Critique

The initial AC module approach and specifications was presented to the array of utility partners for review. Responses from the utility partners were used to modify the specifications and arrive at a consensus as to the best approach for the AC module design.

Task 2 – Module Scale Inverter Design Advancement, Revision 3

The third major design revision of the inverter was performed. Design modifications were made to reduce harmonic current distortion, cost, size and increase efficiency. This design effort was coordinated with Task 3.

Task 3 – Module Scale Inverter Enclosure Development

Packaging of the electronics and enclosure development were done to best integrate the electronics with the PV laminate. An aluminum casting was developed along with a module mounting method which would allow easy service access and repair of the inverter if needed.

Task 4 – UL Testing

Prototypes of the SunSine™300 AC PV Module were evaluated to UL Subject 1741 under UL engineering supervision. A preliminary investigation was conducted by UL to help identify test issues. Prototypes of both the revision 3 and revision 4 SunSine™300s were evaluated and Listed by UL.

Task 5 – 300 Wp PV Module Manufacture

12 PV laminates were manufactured at a rating of 300 Wp to demonstrate the capability. This was accomplished by sorting cells at the PV manufacturer.

Task 6 – Assembly of ten AC PV Module Prototypes

Ten AC Module prototypes using the revision 3 circuit board design were built for the various test processes described in this report.

Task 7 – AC PV Module Testing

Testing of AC Module prototypes included, environmental chamber testing for thermal, humidity/freeze and damp heat. Tests included power quality measurements of harmonic distortion, power factor, anti-islanding performance, and turn on soft starting. Tests also included support of HALT and HAST testing which was co-funded by PVMaT and Sandia National Labs. Tests included EMI testing to FCC Class B requirements. Tests included UL 1741 testing and Listing of the unit.

Task 8 – AC PV Module System Design and Development

Balance of system components were modified for use in AC module systems, including the Residential RoofJacks™ and PV Source Circuit Combiners™. Development of a custom three wire ac power connector was done to allow quick and easy field installation of AC module systems.

Task 9 – Pilot Production of AC PV Modules

Under this task, field evaluation prototypes of the SunSine™300 AC PV Modules were produced to demonstrate manufacturability in a pilot production run of 109 units.

Task 10 – Monitoring and Field Evaluation of SunSine™300s

The units from the pilot production run were shipped to utility partners for installation and evaluation. Some of the systems were instrumented to monitor performance. The results of this task included installations at numerous sites around the country, feedback from utility partners on the system design, and a report on the monitored performance of the system and lessons learned during installation.

Task 11 – Module Scale Inverter Design Advancement, Revision 4

This task included incorporation of lessons learned from previous tasks to the design of the SunSine™300 inverter. This task resulted in a fourth major revision to the SunSine™300 inverter desing, UL Listed, ready for manufacture and commercial introduction.

Task 12 – Production and Quality Review

In this task, a report was prepared in which lessons learned from the pilot production run of the SunSine™300 are summarized. The production process is described. The quality management system that is in place is described.

The SunSine™300 AC Photovoltaic Module

Description

The 1999 National Electrical Code defines an Alternating Current (AC) Module as:

> ***Alternating Current (AC) Module (AC Photovoltaic Module):*** *A complete, environmentally-protected unit consisting of solar cells, optics, inverter, and other components, exclusive of tracker, designed to generate AC power when exposed to sunlight.*

The SunSine™300 is the world's first UL Listed AC Module.

The SunSine™300 is about 4x6 feet in dimensions, weighs 122 pounds, and is rated at 251 Watts AC output at STC, with a maximum AC output of 300 Watts. It is designed for utility interactive operation so that its power is fed back into the electrical grid. It is a non-dispatchable photovoltaic generator of AC power.

Theory of Operation

Figure 1 shows a simplified schematic of the SunSine™300. The AC PV Module includes the photovoltaic cells, glass, laminate, frame, inverter power electronics, controls and aluminum cast housing all in a single environmentally protected unit. The user only has access to AC line, neutral and ground connections.

Power is generated when sunlight strikes the PV cells in the laminate. The laminate is made up of 216 cells, (108 series by 2 parallel, with bypass diodes every 18 cells). The amount of power available depends upon the amount of sunlight striking the unit. During 'normal conditions' of noon day sun, 1000 Watts / m^2, the PV laminate is rated to output 285 Watts DC at it's max power operating point. The max power point is determined by the I-V curve of the PV laminate.

The DC input power is filtered by capacitors C72 & C73, as seen in Figure 1. A buck converter operating at a switching frequency of 100kHz, (composed of MOSFET Q1, diode D1 and inductor L1 as seen in Figure 1), produces a rectified output current waveform. This buck converter is only capable of instantaneous power flow from the DC input to the AC output. For this reason, we say the SunSine300 is a two-quadrant converter, not capable of four-quadrant operation as some other inverters are known to operate.

Since power flow is from the DC side to the AC output, we can not use diodes as a bridge rectifier, we use MOSFETs. MOSFETs in the 'Un-Wrapper' stage are controlled by the micro-controller. This gating is synchronized with the AC voltage waveform so that the voltage seen at the output of the buck converter is a rectified AC voltage. Operation of the Un-Wrapper bridge allows for sinusoidal current to be injected into the isolating transformer, T1.

A solid state relay is designed into the unit so that it may be 'disconnected' from AC power at night time to prevent transformer losses of about 2 Watts, which would otherwise occur all night. This relay also provides a second means of de-energizing the output of the unit when the micro-controller determines the unit should shut down.

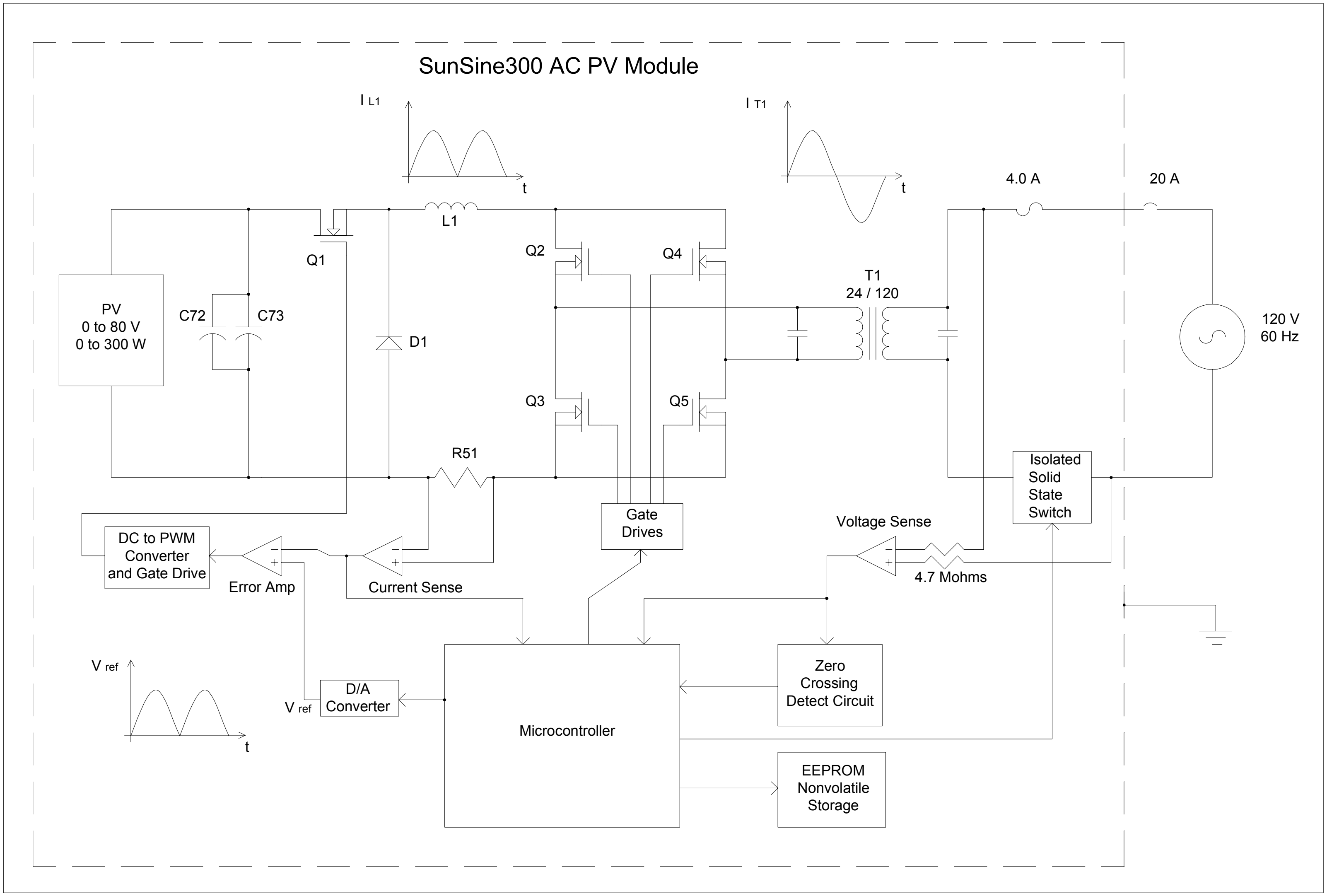

Figure 3 SunSine300 Simplified Schematic

Control of Output Current

The high quality, low THD current output of the SunSine300 is achieved through the use of a hardware feedback loop. This feedback loop controls the gate signal to Q1 of the buck converter. A sense resistor and current-sense amplifier generate a signal which is a rectified version of the output current of the unit. This is compared against a reference signal generated by the micro-controller. This current reference signal has 8-bit resolution at all power levels by use of a proprietary design, and is updated at 210 times per ½ cycle (25.2kHz at 60.0Hz). This hardware feedback loop and simple converter design allow for a well behaved control loop which regulates output current very well, independent of the voltage waveform.

Synchronization with the Utility

The utility voltage is sensed at the terminals of the inverter with a differential amplifier with very high input impedance, 4.7 MΩ. This allows the unit to meet DC/AC dielectric withstand requirements of UL Subject 1741. The AC voltage is input to a zero-crossing detect circuit which generates a 60 Hz square wave precisely in phase with the utility voltage. This square wave is detected by the micro-controller with a 16 bit input capture timer and is used to reset the current reference signal at every zero crossing of the utility voltage. Measurement of utility frequency is determined by the time elapsed from zero crossings over each full cycle. This measurement of utility frequency is used to determine the update rate of the current reference signal so that the reference returns to zero at the next zero crossing.

Measurement of Utility Voltage

The voltage is sampled 32 times each ½ cycle by an 8-bit A/D converter in the micro-controller. The micro-controller computes utility voltage every full cycle. This computed voltage is compared against the fast, medium, and slow speed trip set points. Note, the fast trip set point is compared every ½ cycle. Appropriate counters are incremented if a set point is exceeded, and decremented or left at zero if not exceeded. When a counter exceeds the programmed time to trip limit, the unit is shutdown.

SunSine™300, AC Model

First order modeling of the SunSine300 is achieved by treating the inverter on the low voltage side of the transformer as an ideal AC current source. The AC current source must by synchronized with the primary side voltage. The AC current source is a low THD sine wave, independent of utility voltage. Per unit impedances are shown in parentheses (). One per unit (1pu) is based on 300 VA at 120 V, which is 48Ω.

The EMI capacitors, reflected to the transformer primary, may be lumped together as one 0.48µF (115pu) capacitor. The transformer magnetizing current has been measured and a value computed based upon the 60 Hz reactive component. This magnetizing inductance, referred to the transformer primary is 48.3 H (379pu). The winding resistance of both the primary and secondary of the transformer has been measured, and referred to the primary is 2.07Ω (0.043pu). The no load loss of the transformer was measured and corresponds to an effective resistance of 5,230Ω (109pu).

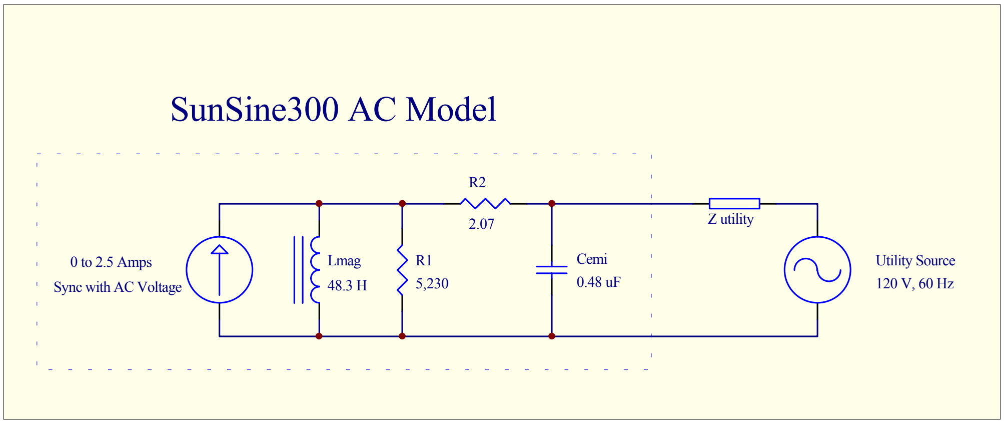

Figure 4 SunSine300 AC Model

Operation during Utility Short-Circuit

During a utility short circuit, the output of the inverter current remains well regulated. This lasts for about ½ cycle before the unit trips on under voltage, loss of zero crossing, or frequency trip. The fast under voltage trip is presently set at 40 volts. Normally, the output of such an inverter is not controllable at zero output voltage, but the transformer provides enough impedance that the inverter is able to maintain current regulation. Therefore, the unit does not output a large current surge during a utility short circuit.

'Fail Safe' Design

In the design of the SunSine300, we have followed the following premise:

> *If any single component should fail in either the short or open condition, and that component may impact safe operation of the unit, then the unit shall shutdown and cease to operate.*

See the UL 1741 section under Test Results for more information.

Specifications

Construction

Solar Cells	100 mm^2 (3.94") Crystalline
Number of Cells	216
Encapsulant	Advanced (not EVA)
Front Cover	3 mm (1/8") tempered low-iron glass
Back Cover	3 mm (1/8") tempered glass
Frame	Aluminum
Inverter Case	Cast Aluminum

Certifications and Test Methods Applied

Safety	UL1703 (PV) UL1741 Class A Fire Rated
EMI/RFI	FCC Class B per CISPR 22 B BS EN 55022
Product Reliability	HALT/HAST
Other	IEC 503 (PV)

Environmental Conditions

Max Cell Temp[1]	90 °C (194 °F)
Min Cell Temp	-40 °C (-40 °F)
Relative Humidity	0 - 100%
Tested Wind Conditions	195 km/h equivalent 120 mph equivalent
Max Ambient Air Temperature[2]	60 °C (140 °F)
Min Ambient Air Temp	-40 °C (-40 °F)

Note 1: Under full sunlight, cell temperature is typically 25-30 °C above ambient.
Note 2: Above this temperature, electronic thermal limiting may limit output power.

Standard Packaging - Crate

Minimum Quantity	20
Crate Weight	1282 kg (2826 lbs)
Crate Height	2.08 m (83")
Crate Width	1.16 m (46")
Crate Length	1.42 m (56")

Physical

Length	1892.3 mm (74.5")
Width	1282.7 mm (50.5")
Weight	55.3 kg (122 lbs)
Maximum Tilt Angle	90 degrees

Features

Over-Temperature Shutdown
Maximum Power Tracking
Fully Automatic Operation, Protection and Reset
Morning and Evening Start-up and Shutdown
Zebra (proprietary) Active Anti-Islanding Protection
Built-in Transformer Isolation
Over/Under Voltage and Over/Under Frequency Protection

Electrical (All Models)

Rated Voltage	120 Vac
Operating Voltage	104 - 132 Vac
Rated Frequency	60 Hz
Operating Frequency	59 - 61 Hz
Max Output Current[3]	2.5 A
Max Number per 20A Branch Circuit	6
Absolute Max AC Output Fault Current	4.0 A

Electrical (All Models)

Max Output Power[3]	300 W_{ac}
Output Power[3,6] @STC[7] @PTC[8]	251 W_{ac} 232 W_{ac}
Current THD 100% Power 15-100% Power Individual Harmonics 15-100% Power	 < 2% (Typ) < 5% (Max) < 3% (Max)
Power Factor 40-100% Power	 > 0.95
Power Variation vs. Temperature	-1.227 $W_{ac}/^{o}C$
Electrical Isolation AC Output - Ground AC Output - PV PV - Ground	 2300 V_{pk} 2300 V_{pk} 1640 V_{pk}
Night Time Losses	< 0.3 W_{ac}
Max Over-current Protection[4]	20 A

Note 3: May vary by +/-5%
Note 4: Provided by Installer.

Typical Output Power vs. Temperature[5]

Ambient Air Temperature[5]	SunSine™300 Power Output
-40 °C (-40 °F)	300 W_{ac}
-10 °C (14 °F)	268 W_{ac}
10 °C (50 °F)	245 W_{ac}
25 °C (77 °F)	228 W_{ac}
50 °C (122 °F)	197 W_{ac}

Note 5: Assumed Cell Temperature is 27 °C above air temp, Irradiance = 1000 W/m^2, AM=1.5.
Note 6: These specifications are based on use of 285 Wdc rated PV laminates. Higher laminate ratings may be available.
Note 7: STC, Standard Test Conditions, 1000 W/m^2 plane-of-array irradiance, air mass 1.5 spectrum, cell temperature 25 °C.
Note 8: PTC, PVUSA Test Conditions, 1000 W/m^2 plane-of-array irradiance, air mass 1.5 spectrum, 20 °C ambient air temperature, wind speed 1 m/s.

SunSine™300 Test Results

Power Quality

The tests in this section were conducted on an inverter from the first production run. The unit serial number was 000039. These results should be typical of the power quality of units shipping today. This unit was operating with firmware version 1.44. This is the only firmware version which has been released as of December 1998 for production.

Current THD vs. Output Power

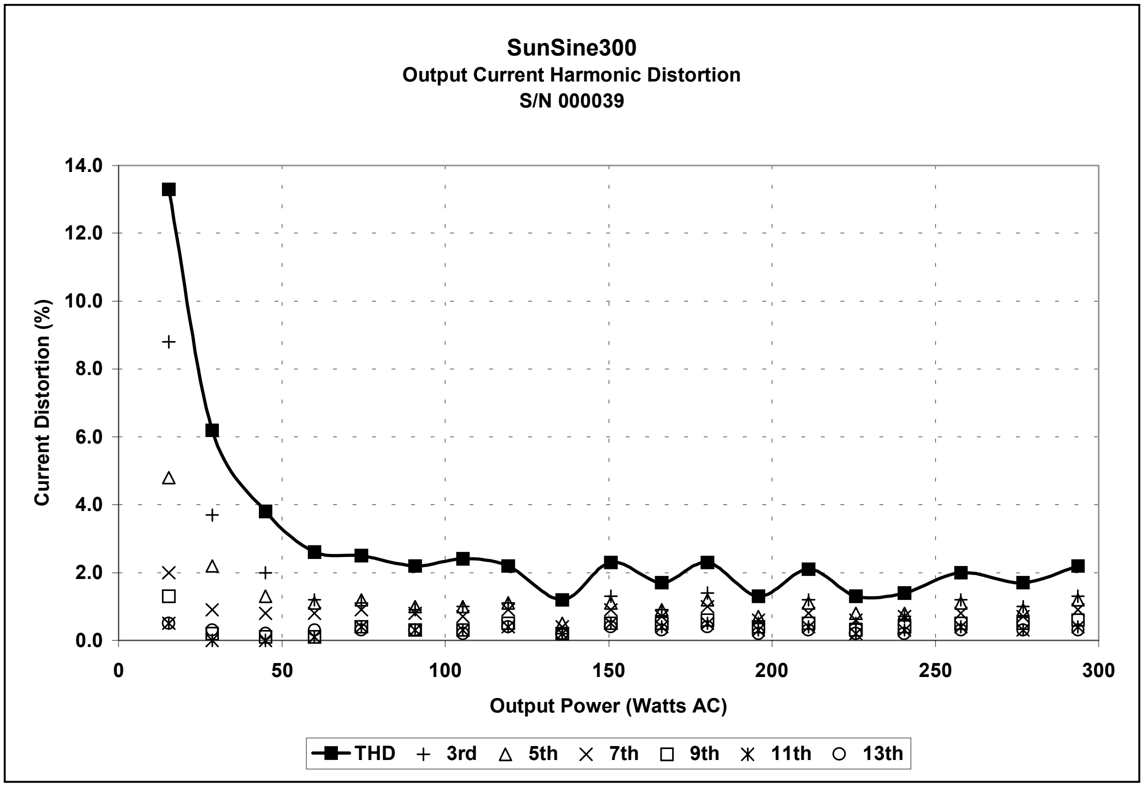

Figure 5 SunSine™300 Harmonic Current Distortion

Figure 5 above shows output current THD as well as data points for individual odd harmonic amplitudes up to the 13th harmonic. THD is shown as a percentage of the actual output current, not the full scale rated output current. These levels for harmonic distortion are well below the limits set in IEEE-P929, Draft 6, September 1998. The reason for the fluctuations in THD seen in the graph above is due to operation of the Zebra™ anti-islanding method. If time averaged THD measurements were displayed, the chart would be smoother in appearance. These THD measurements were made using about 3 cycles of waveform data.

Power factor vs. Output Power

SunSine™300 Power Quality Measurements
Unit s/n 000039

Output Power	**Reactive Power**	**Power Factor**		**Voltage** (Utility)		**Current** (Inverter)		**Odd Harmonics**					
								3rd	**5th**	**7th**	**9th**	**11th**	**13th**
W	VARs	PF	dPF	Volts	% THD	Amps	% THD	%	%	%	%	%	%
293.7	0.178	1.00	1.00	120.2	5.1	2.448	2.2	1.3	1.2	0.9	0.6	0.4	0.3
276.8	2.663	1.00	1.00	119.8	5.1	2.314	1.7	1.0	0.9	0.7	0.5	0.3	0.3
257.9	1.670	1.00	1.00	120.1	5.1	2.152	2.0	1.2	1.1	0.8	0.5	0.4	0.3
240.5	4.135	1.00	1.00	120.3	5.0	2.003	1.4	0.7	0.8	0.7	0.4	0.3	0.2
225.7	4.750	1.00	1.00	120.2	5.0	1.881	1.3	0.5	0.8	0.6	0.3	0.2	0.2
211.2	1.603	1.00	1.00	120.0	5.1	1.762	2.1	1.2	1.1	0.8	0.5	0.4	0.3
195.8	4.155	1.00	1.00	119.9	5.1	1.635	1.3	0.5	0.7	0.6	0.4	0.3	0.2
180.3	1.003	1.00	1.00	119.8	5.0	1.508	2.3	1.4	1.2	1.0	0.6	0.5	0.4
166.2	2.268	1.00	1.00	119.8	5.0	1.390	1.7	0.9	0.9	0.7	0.5	0.4	0.3
150.7	1.068	1.00	1.00	119.5	5.1	1.263	2.3	1.3	1.1	0.9	0.5	0.5	0.4
135.8	3.963	1.00	1.00	119.1	5.1	1.142	1.2	0.2	0.5	0.4	0.2	0.2	0.2
119.2	0.715	1.00	1.00	119.1	5.1	1.002	2.2	1.1	1.1	0.9	0.5	0.4	0.4
105.3	2.073	1.00	1.00	119.1	5.0	0.886	2.4	1.0	1.0	0.7	0.3	0.3	0.2
90.80	1.662	1.00	1.00	119.2	5.0	0.763	2.2	0.9	1.0	0.8	0.3	0.3	0.3
74.34	1.025	1.00	1.00	119.1	5.0	0.625	2.5	1.1	1.2	0.9	0.4	0.4	0.3
59.91	1.520	1.00	1.00	119.0	5.0	0.504	2.6	1.2	1.1	0.8	0.1	0.1	0.3
44.92	1.543	1.00	1.00	118.7	5.1	0.379	3.8	2.0	1.3	0.8	0.1	0.0	0.2
28.57	0.949	1.00	1.00	118.6	5.1	0.242	6.2	3.7	2.2	0.9	0.2	0.0	0.3
15.34	0.744	0.99	1.00	118.8	5.1	0.131	13.3	8.8	4.8	2.0	1.3	0.5	0.5

The table above shows the data that was used to generate the plot in the previous section on harmonic distortion. The table also shows that the power factor of the unit measured in both PF and dPF is unity, 1.00 for practically its entire range of output powers. The variation in VARs and THD seen in the table above is due to operation of the Zebra™ anti-islanding method that forces small variations in the output waveform of the inverter.

One may also notice the increase in utility voltage as the output power of the inverter increases. These tests were done in a lab in a commercial building. In addition, the utility voltage passes through a variable auto-transformer to allow tests at varying voltage levels. Therefore, the impedance of the utility in these tests is somewhat higher than what might be typical in installations.

The voltage THD reading of 5.1% is typical for service voltage from the utility in the commercial building in which these tests were done. The voltage THD does not vary as a function of inverter output power and does not depend on whether the inverter is connected or not. It is a measure of the power quality of the local utility service.

Soft Start Ramp to Full Power

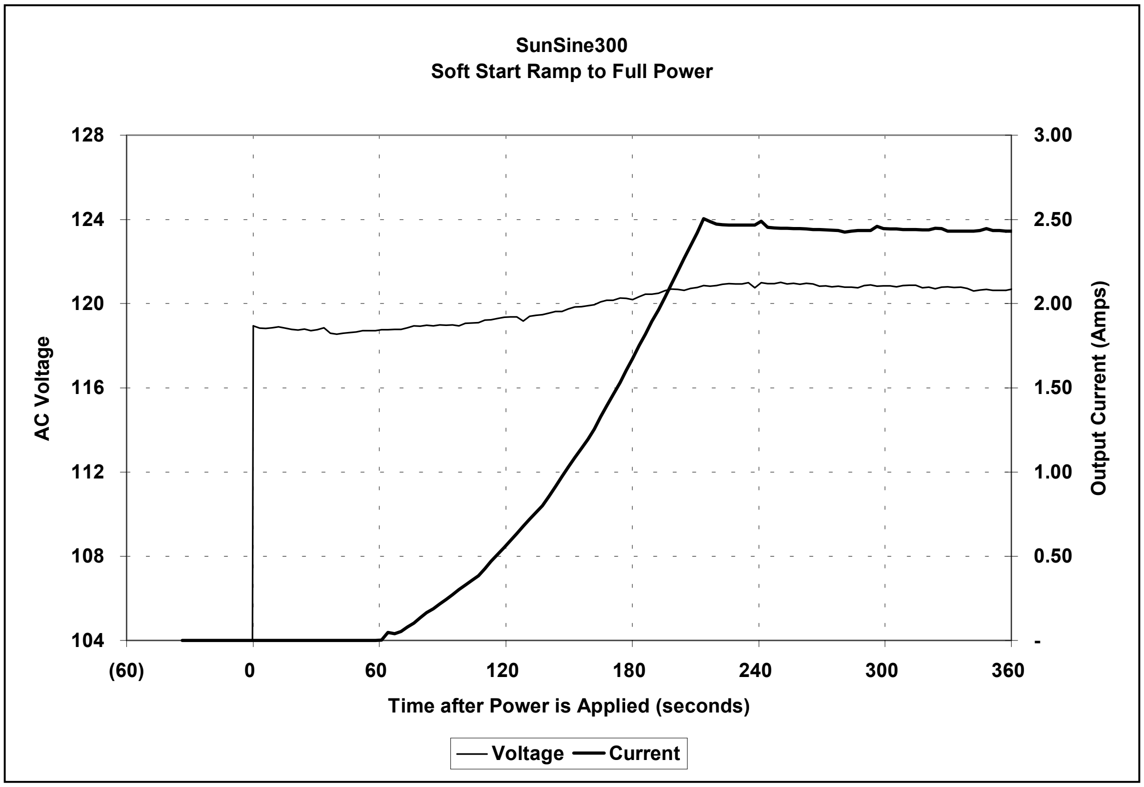

Figure 6 SunSine300 Soft Start Ramp to Full Power

Figure 6 above shows the smooth startup of the inverter after connection of utility power. This is actual test data taken on a SunSine™300 inverter under lab test conditions. The same soft start function occurs after a disturbance has caused the inverter to shut off. 60 seconds after power is applied, the inverter begins to draw current from the utility. For the next 10 seconds the transformer is connected to the utility and the inverter is waiting to start power conversion. At 70 seconds, the inverter begins a slow ramp up of output power until it reaches the maximum power output capable from the PV laminate. In this case the unit was able to ramp up to it's maximum rated output of 2.5 Amps.

One will also note the increase in line voltage as the inverter increases output power. This is due to resistances in the branch circuit wiring between the inverter and the 'infinite bus utility'. Most of that resistance is between the inverter and the main distribution panel in the lab facility where these tests were conducted.

The soft start function is desirable to minimize potential impact for voltage flicker when large numbers of PV systems begin to turn on after a utility outage.

Nighttime Losses

The control electronics for the SunSine™300 are powered from the PV input to the inverter. At night the control electronics are off and the inverter is disconnected from the utility. There remains a 470KΩ resistor connected across the utilty input. There is also a 0.1µF capacitor in the EMI filter section connected to the utility. At night the inverter will typically draw 0.03 Watts and 0.54 Vars due to this resistor and capacitor.

AC Module Efficiency

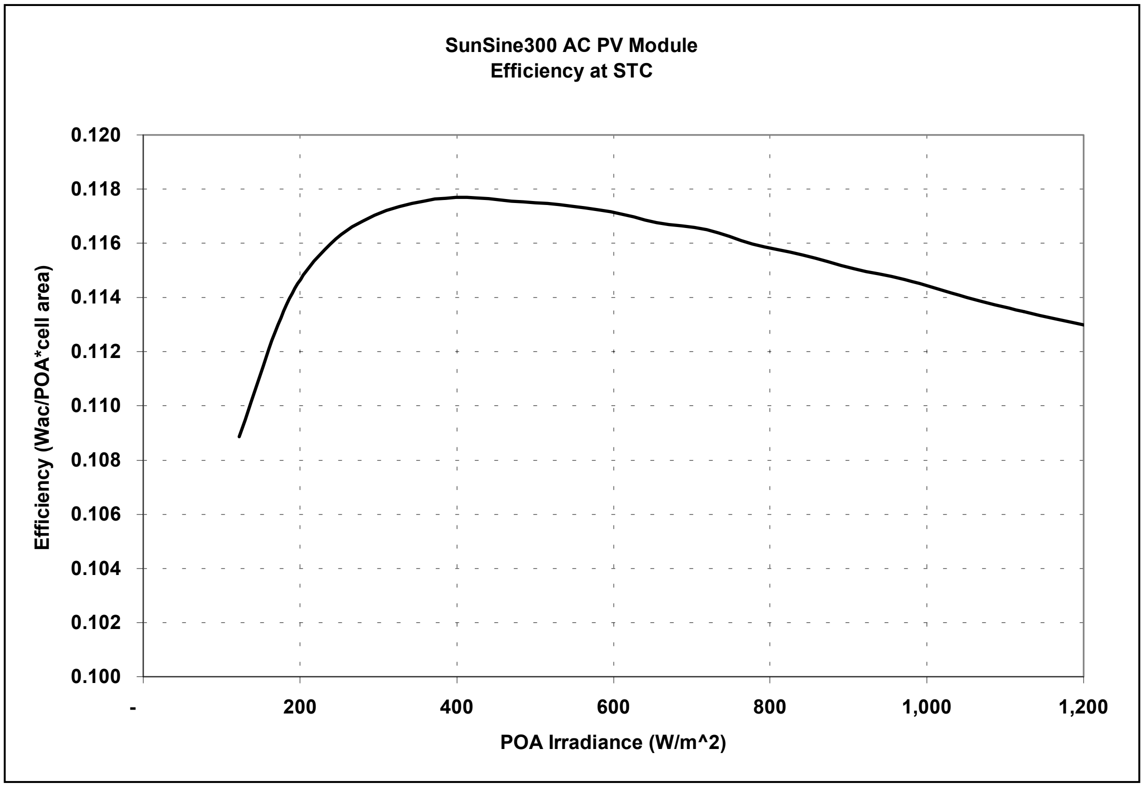

Figure 7 SunSine300 AC PV Module Efficiency at STC

Figure 7 above shows the efficiency of the SunSine™300 AC PV Module. It is based upon a total cell area of 2.16 m^2. This figure is shown for operation at standard test conditions (STC). The data is based upon actual inverter efficiency measurements taken in the lab, combined with known operating data of the PV laminate at STC. Peak efficiency of the AC module is roughly at the midpoint of its range of operation. The unit can operate properly during irradiance conditions over 1000 W/m^2. To determine operation characteristics at conditions other than STC, apply the temperature coefficients found in the specifications section.

Highly Accelerated Stress Testing (HAST)

The objective of this test process is stated in the test report:

> *Poor reliability, low MTBF, frequent field returns, high in-warranty costs, and customer dissatisfaction are of the result of design and/or process weaknesses, even if a product has successfully passed qualification tests and burn-in. The product was subjected to the HAST process to uncover design and/or process weaknesses. During the HAST process, the products were subjected to high stress levels brought on by thermal, humidity, and pressure. Throughout the HAST process, the intent was to subject the product to these stimuli well beyond the expected field environments to determine the operating and destruct limits of the product. The same failures which typically show up in the field over time at a much lower stress levels show up quickly in these short term high stress conditions. This HAST was primarily a discovery process. In order to improve the product's reliability and increase its MTBF, the root cause of each of the failures noted needs to be determined and the problems corrected until the fundamental limit of technology for the product can be reached. This process will yield the widest possible margin between product capabilities and the environment in which it will operate, thus increasing the product's reliability, reducing the number of field returns and realizing long-term savings.*[1]

Two test samples of the SunSine™300 main circuit board and transformers where placed in the test chamber. These units were subjected to 110 °C and 85% RH resulting in an atmospheric pressure of 1.242 kg/cm^2 gage. The test duration was 206 hours, with a 3 hour ramp-up to the setpoints, a 200 hour dwell at the desired setpoints, and a 3 hour ramp-down to room ambient conditions. Both AC and DC power were applied to the test units, and they began the test operating at 3% rated output. Operation was not monitored during the test. When the test finished, one of the units was still operating, and the other was not. The unit which was still operating had been fabricated using a proprietary process, and this test was confirmation of the value of using that process.

Numerous potential failure modes were uncovered during the test, and corrective action was taken in the design of the unit or source of components.

Sandia National Laboratories contracted directly with QualMark to provide the HALT and HAST testing service. Preparation of test samples, engineering and evaluation of the test results which were used in part to help pass UL testing, were all funded by PVMaT.

The HALT and HAST testing was initially suggested by Sandia National Laboratories and was co-funded by PVMaT and Sandia.

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[1] QualMark Corporation, *HAST REPORT No. TR-0000546:HAST*, March, 1997, Confidential report submitted to Ascension Technology, Inc.

Highly Accelerated Lifetime Testing (HALT)

The objective for HALT testing is basically the same as that for HAST testing, however the process is different. The HALT test regimen applies thermal and mechanical vibration stress to the unit under test. Part of the objective is to determine both the operational and destruct limits of the product. During the testing, when a limit is found, such as vibration causing leads on a component to fail, that failure is repaired and then masked so that operation can go beyond that limit to find the next failure mode. Masking of that type of failure mode might be done by applying epoxy to the repaired leads so that they don't break again when vibration is increased. The goal is to find all of the failure modes of the product, determine their root causes, and then correct those causes so that the product has reached the limits of its technology.

The HALT process begins by reducing temperature in 10 °C steps lasting ten to fifteen minutes until you reach the low temperature destruct limits, or the limits of the test chamber (-100 °C). During the HALT testing, whenever temperature is changed, it is changed very quickly. Temperature change rates can reach 60 °C / minute rates of change. The high rate of change of temperature is also one of the stresses that the product will see and helps to force failures in the product.

After the cold step test, there follows a hot step test to determine the high temperature limits of the product. The next sequence is a rapid thermal transition test, where the temperature is cycled between a high and low temperature limit at a high rate of change. Multiple cycles are performed. Then the vibrational step test is performed where vibration is increased at 10 G (rms) per test point for ten minutes. The final test was a combined environment where the rapid thermal transition test with high and low temperature set points is combined at the same time as vibrational testing. Below is a summary of the test results found with the SunSine™300 as tested:

SunSine™300 **HALT Test Results** (pre production version)	
High Temperature Destruct Limit	120 °C
High Temperature Operating Limit	90 °C
Low Temperature Operating Limit	-70 °C
Low Temperature Destruct Limit	< -90 °C
Rapid Thermal Transitions Operating Limit	-55 °C to 85 °C at 45 °C / minute
Vibration Operating Limit	20 G (rms)
Vibration Destruct Limit	20 G (rms)
Combined Thermal and Vibration Operating Limit	-55 °C to +85 °C at 10 G (rms)
Combined Thermal and Vibration Destruct Limit	-55 °C to +85 °C at > 35 G (rms)

An operating limit means that when the limit is exceeded, the unit ceases to operate within specifications. When the stress is removed and returns to within the normal operating limits, proper operation of the unit returns. A destruct limit is one that if it is exceeded, the unit will no longer operate properly even if the stress is removed. After these tests were completed, changes were made to the design of the SunSine™300 to correct as many of the failure modes as possible.

Anti-Island Testing – Development of the Zebra Anti-Islanding Method

During the development of the SunSine™300 it was recognized early on that some form of anti-island protection other than the standard voltage and frequency trip set points would be required. Anti-Island testing was to be performed as part of the UL Listing process. Tests were conducted which showed that it was rather easy to force an island to occur in a lab environment under controlled conditions if all that was implemented were voltage and frequency trip set points in the inverter. A search of some of the existing literature was conducted and a method was developed which we called the Zebra™ Anti-Islanding Method. This name was chosen early on since we originally decided to keep the specifics of the method proprietary. Since that time we have concluded that since this is considered a safety issued for utilities and customers, it is more important for the anti-islanding methodology to be disclosed and open for scrutiny.

The Zebra™ anti-islanding method is an active perturb and observe method. The output current waveform is shifted in frequency from the power-line frequency. There are two values of frequency shift used, both of which are small and impart minimal harmonic distortion. Each of these two values, call them A and B, are applied to the output waveform on a cycle by cycle basis following a predetermined pattern. The pattern is:

AAAA AAAA BBAA BBBB BBBB AAAA BA

The current waveform is reset to synchronize with the voltage waveform at every zero crossing of the voltage. This maintains essentially synchronous operation between the output current and utility voltage.

The frequency of the utility is measured from a zero-crossing-detect circuit looking at the voltage waveform. Using a mathematical correlation technique, when the frequency variations of the utility voltage coincide with the frequency variations of the output current control to a strong enough degree, the unit shuts off. When the inverter is connected to a utility system, the utility system maintains good regulation of the system frequency no matter what the inverter does. When the utility is no longer connected, a strong correlation exists between the output current frequency shifting and measured utility frequency. This is detected by the unit and forces the unit to shut down.[2]

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[2] Kern G. A. "SunSine300, Utility Interactive AC Module Anti-Islanding Test Results", *Proceedings of the 26th IEEE PVSC*, Anaheim, CA, September 1997.

UL 1741 Testing

The SunSine™300 is the first AC PV Module to undergo and pass the UL 1741 standard. Ascension Technology worked with UL to define test methods for applying the standard to this product. Prior to beginning the test sequence described below, the inverter components and design was evaluated by UL to ensure it met the design requirements listed in UL 1741. This design review included verification of the use of recognized vendors for supply of the printed circuit boards and review of the circuit board to ensure it met the clearance and creepage requirements for a safe product.

Below is a description of the tests conducted under UL supervision to ensure the SunSine™300 met UL 1741 requirements as a safe product.

Grounding Resistance Test

A 25 amp AC current is passed between the grounding conductor in the output cables for the unit and any exposed metal in the unit. The resistance measured by this test was 0.03Ω and the test limit is 0.1Ω.

Strain Relief Test

This test is performed to ensure proper cable strain relief of the two AC output power cables. A 35 lb pull was applied to one of the cables, in any angle the contstruction would permit. The pulling force was applied for 1 minute with no sign of movement in the output cable.

Harmonic Distortion Test

This test is conducted to ensure that the unit provides a clean sinewave output current. This test was conducted at full power and operating from a DC power supply. The AC output was connected to an AC branch circuit through a resistance that represented 2% impedance based on the inverter rating. This test was conducted with a unit rated for 240 Volts. The power rating of the unit is 300 Watts. The test resistance used was R = 0.02 * V^2 / P = 0.02*240^2/300 = 3.8Ω.

The total harmonic distortion of the output current waveform was measured as 1.8%. The maximum single harmonic was measured as 1.2%. The limits for this test were 5% and 3% respectively as specified in IEEE 929.

Output Ratings Test

The purpose of this test is to verify the nameplate ratings of the unit. This test also verified that the unit did not inject any more than 0.5 percent of its rated current as DC current into the utility. The unit tested had a rating of 120 Volts, 2.5 Amps, 300 Watts, unity power factor. The measured output was 123.6 Volts (connected to a branch circuit controlled by the utility), 300.6 Volt-Amps, 2.43 Amps, 0.99 power factor. The measured output current was not more than 110 percent of it’s rating. The measured DC current output was not more than 0.5 percent (12.5 milliamperes) of the inverter’s rated output current.

Temperature Test

The purpose of this test is to ensure that all critical components operate at or below their manufacturer’s specified maximum operating temperature when the inverter is operating at it’s specified maximum operating temperature. This test was conducted at two different temperatures, controlled by a temperature chamber.

At 50 degree C ambient, the inverter was operated at an output of 117.5 Volts, 2.49 Amps, 293 VA. This test ran for 18 hours in this condition. At the end of the test, all components were operating within their specified operating limits.

At 60 degree C ambient, the inverter was operating at an output of 117.6 Volts, 1.83 Amps, 215 VA. This test is more representative of what the AC module would operate at with such a high ambient temperature. In this high ambient temperature, the PV module output power is reduced due to the temperature coefficients of the PV cells. Since the inverter and PV module constitute the AC module, this approach was allowed so that a realistic maximum operating ambient temperature rating of 60°C could be achieved.

Dielectric Voltage Withstand Test

Immediately after the temperature test, the inverter was subjected to a high voltage dielectric withstand test. The purpose of this test is to ensure that the unit maintains electrical isolation between the electrical circuits and ground. A potential of 1640 volts DC was applied between the DC input to the inverter and ground. A potential of 2300 volts DC was applied between the AC output circuit and ground. A potential of 2300 volts DC was applied between the DC input and AC output circuits. Each of these three test potentials were applied for a minimum of 60 seconds without electrical breakdown.

This dielectric voltage withstand test is repeated in each of the 'abnormal' tests listed later. The purpose is to ensure spacings and insulation remain intact even after occurrence of abnormal faults in the unit.

Anti-Islanding Test

The anti-islanding tests were conducted using the best information available to UL at the time of testing with respect to islanding of inverters. At present, more information is known and understood about effective test methods for proving an inverter will not run-on in island conditions.

Method A. The utility voltage was reduced to 86% of nominal and the time for the inverter to cease operation was measured. Two tests were conducted. In the first test, AC voltage was reduced to 102.6 volts and the inverter de-energized in 1.7 seconds. In the second test, AC voltage was reduced to 103.3 volts and the inverter de-energized in 1.7 seconds. The time limit to pass this test was 2 seconds.

Method B. The utility voltage was increased to 110% of nominal and the time for the inverter to cease operation was measured. Two tests were conducted. In the first test, AC voltage was increased to 133 volts and the inverter de-energized in 2 seconds. In the second test, AC voltage was increased to 134 volts and the inverter de-energized in 1.68 seconds. The time limit to pass this test was 2 seconds.

Method C. The utility frequency was decreased from 60 to 59 Hertz by operating off a simulated utility. The time for the inverter to cease operation was measured. In this test the inverter ceased operation within 2 seconds.

Method D. The utility frequency was increased from 60 to 61 Hertz by operating off a simulated utility. The time for the inverter to cease operation was measured. In this test the inverter ceased operation within 2 seconds.

Method E. The utility voltage is decreased and the time for the inverter to shut off was measured. When the voltage was decreased to 97.2 volts, the inverter shut off in 1.7 seconds (102 cycles). When the voltage was decreased to 94.8 volts, the inverter shut off in 0.173 seconds (10 cycles). When the voltage was decreased to 72 volts, the inverter shut off in 0.031 seconds (2 cycles). When the utility was disconnected, the inverter shut off in 0.0045 seconds (1/2 cycle).

Method F. The inverter was operated at full power. An inductive and resistive load was connected in parallel with the inverter, on the inverter side of the utility disconnect switch. The load was adjusted to minimize the net watts and vars flowing between the utility and the inverter/load. The resistive load was 50Ω. The voltage was approximately 120 volts. The net power at the switch was measured as 1 watt and 5.5 vars. The inverter shut down 0.27 seconds (16 cycles) after the switch was opened.

Methods A-F. In each of these tests, the inverter would not attempt to restore operation until the utility was within normal operating conditions for 70 seconds. As long as the utility remained off, the inverter reamined off as well.

Loss of Control Circuit Test

During this test, power was removed from the control circuits by two means. First, power was removed by opening a connection which fed power to the control circuit power supply circuits. In this case, it took 0.024 seconds for the inverter to shutdown and cease operation. In the second case, the 5 volt DC supply bus which powers the microcontroller, was shorted, disabling the microcontroller. In this case, the inverter shut down in less than 0.001 seconds. In both cases, the fault was removed and the inverter returned to normal operation. The inverter did wait 70 seconds before resuming power conversion, this is the normal time-out in the unit to ensure the utility is within normal operating limits of voltage and frequency.

Abnormal Tests

The following tests are considered abnormal fault condition tests. In these tests, various faults are forced to occur in the unit. The unit is covered with a cheese cloth and tissue material that will record any evidence of fire, heat or the like escaping from the units' enclosure. The unit is also operated on a soft pinewood that will show evidence of charring were the unit to get too hot. If any of these materials show evidence of charring, that would constitute failure of the test.

Also during these tests, the inverter is connected to ground through a 3-Amp fast-blow fuse. If the fuse blows during any of these tests, that is evidence of excessive ground fault current and the unit fails the test.

At the end of each of these tests, the unit is subjected to the dielectric-voltage-withstand test above. The unit must maintain electrical isolation from ground after each of these tests. If it does not, that is grounds for failure of the test.

In all of the abnormal tests below, the unit passed.

Output Overload-Utility Interactive Abnormal Test

The inverter was operated at the highest power level possible without blowing the internal protective fuse (4.0 Amps) and without component failure. The idea is to get the inverter to malfunction in a way so that it operates as hot as possible to see if there is a risk of fire or electric shock. Multiple faults had to be imposed on the inverter in order to get it to run in this condition. The internal temperature sensor had to be disabled so that it gave a constant reading within the normal temperature limits of the unit. The output current limit firmware setting was increased to just below the 4.0 amp fuse limit to allow operation beyond 2.50 amps.

During this test, the utility voltage was set to 90% of nominal. At the end of the test, the inverter output current was 3.62 Amps. This test was operated until thermal stabilization or 7 hours, whichever came first.

Output Short Circuit Abnormal Test

With the unit operating normally, a short was applied between line and neutral using a knife blade switch. When the short was applied, the inverter shut down immediately and the 20A branch circuit breaker opened. The internal fuse in the inverter did not open. This test was noted as 'uneventful'. Although not part of the UL test requirement, when the short was removed and the branch circuit breaker was reclosed, the inverter did return to normal operation.

Component Malfunction Abnormal Test

This test is designed to simulate single component faults. The inverter design was evaluated to determine components, which if they failed, would most likely cause a risk of fire or electric shock. Seven components were identified and either shorted or open circuited to cause failure of the unit. During all of these tests, there were no adverse indications.

Electrolytic Capacitor Fault Abnormal Test

The purpose of this test is to make sure that the unit remains safe, even when an electrolytic capacitor fails. This test is performed on one of the large storage capacitors in the unit. Power is removed from the unit under test. One of the storage capacitors is inserted in the circuit with incorrect polarity. DC and AC power is applied to the unit under test. When this occurs, a reverse voltage is applied across the capacitor, casing the capacitor to fail within a few minutes or seconds. When an electrolytic capacitor fails in this way, it can generate a great deal of heat, will typically rupture, and emit vapors and liquid electrolyte. The electrolyte then condenses on the cooler surfaces nearby, causing a loss of insulation between the electrical circuits and ground.

This test was performed on a unit held in both the horizontal and vertical orientations. The test unit passed the dielectric withstand test in both these positions.

Temperature Cycling Test

This test is the same test from UL 1703 that is applied to DC PV modules for UL testing. The inverter must also meet this test requirement since it is mounted on the rear of the pv laminate. This test consists of 200 cycles. Each cycle consisted of a transition from 25°C to –40°C, dwell at –40°C, transition from –40°C to 90°C, dwell at 90°C and a transition to 25°C. Each cycle lasts approximately 4 to 6 hours, for a total test time of about 1000 hours.

At the end of the test, the unit remained intact and passed all dielectric tests. Leakage current was less than 1mA.

Humidity / Freeze Test

The humidity test is similar to the temperature cycling test above, except for the temperature and humidity set points. This test consists of a minimum of 10 test cycles. Each test cycle consisted of a transition from 25°C to 85°C, dwell at 85°C and 85% RH, transition from 85°C to –40°C, dwell at –40°C, and transition back to 25°C. Each cycle lasts for about 24 hours, giving a total test time of about 240 hours. This is also the same test as is specified in UL 1703.

At the end of the test, the unit remained intact and passed all dielectric tests. Leakage current was less than 0.5mA and was measured as 0.3mA.

Water Spray (Rain) Test

This is also the same test that UL applies to DC PV modules in UL 1703. In this case, a set of three water spray heads are adjusted to spray water in a particular pattern. The unit under test is located so that it will test if water can enter the inverter enclosure. Inside the inverter, dry paper patches were placed to record if any water got on any of the electrical components or collected in the bottom of the inverter case. This test was run in both vertical and horizontal orientations of the AC module, and at direct vertical or 60 degree angle of tilt.

There was no collection of water in the enclosure or on the electrical components.

Capacitor Stored Energy Test

The purpose of this test is to ensure that there is no significant stored energy in the unit 5 seconds after removal of all power. The only place were stored energy can remain in this unit is in the DC side storage capacitors. Using a digital storage scope, the voltage across the capacitors was measured when power was removed. At 5 seconds after removal of power, the voltage was 34V. The total capacitance is 6618uF, leaving a total stored energy of 3.83 Joules. This is less than the limit of 20 Joules.

Tensile Strength Test

The tensile strength test was performed on the o-ring material used to form a seal between the inverter and the module mounting plate. This is to make sure that the material retains it's sealing properties with aging. The material properties of average tensile strength (psi) and average elongation (percent) were measure upon receipt of material and after aging. Aging of the material was done for 7 days at 136°C. After aging, the material retained at least 60% of the as-received values.

Inverter Securement Test

This test is to ensure that the inverter remains attached to the PV laminate. This test was conducted after both the humidity cycle test and the temperature cycle tests. In addition to the inverter weight of about 22 lbs, and additional 65 lbs was added as pulling force. The force to cause separation was at least four times the weight of the inverter unit. The inverter mounting plate did not pull free from the PV module.

Electromagnetic Compatibility (EMC)

TUV Product Service conducted tests of the complete SunSine300™ AC module at their Pinewood, Colorado outdoor test site. Conducted emissions were tested between 0.150 to 30.0 MHz. Radiated emissions were tested between 30.0 to 1000.0 MHz. The test criteria applied was EN55022 Class B, also known as CISPR 22 Class B. The U.S. FCC allows use of data collected using this test criteria. We used this test method since it is more stringent than standard FCC Class B limits and may also be used for international test requirements.

Tests were conducted at 120 Volts 60 Hertz. The passing margin for conducted emissions was 15 dB at 0.210 MHz. The passing margin for radiated emissions was 3.7 dB at 170 MHz. This test method and results meet the following requirements:

SunSine™300 **EMC Compliance**
Federal Communications Commission part 15 Class B VCCI Class B CISPR 22 (1993) Class B

SunSine™300 Production

There are two major components in the SunSine™300 AC Module, the inverter and the PV laminate.

Inverter Manufacturing

During the course of this program, several means for manufacturing the inverter were considered. First, would have been to build and establish our own facilities, management, people, etc. to do the manufacturing. Early in the process we recognized the significant costs involved in this approach so we looked for other possibilities. The second approach was to hire a contract manufacturer who may not necessarily have experience with inverters or the PV industry. A relationship was established with such a company, and they built prototype units for us. Before production began, they decided to exit the contract manufacturing business and concentrate on production of their own product line. This left us looking for a means to manufacture the inverter again. The third approach was to team with a manufacturer who was familiar with inverters and the PV industry and who would be capable of maintaining strict quality control. Fortunately, we found such a company in Omnion Power Engineering Corporation of East Troy, Wisconsin.

Omnion was able to understand the product and its requirements immediately. Hiring Omnion to do the inverter production left Ascension Technology free to apply our resources to marketing and business strategy for the SunSine™300 product. At the time we chose to start working with Omnion, they were in the midst of ISO-9001 Qualification, which is a significant commitment to Quality.

Our experience in working with Omnion over the last year has been very good. To this date and to our knowledge, there have been no failures in the field related to SunSine™300 inverter production. In the first year of production, approximately 300 units have been built. The present inverter production capacity is 2500 units per year.

At the present time, we offer a two (2) year standard limited warranty on the inverter, with an option to purchase a five (5) year extended warranty.

PV Laminate – Inverter Integration

The PV laminate is just as critical a component as the inverter. In the case of an AC PV Module, the inverter is integrated directly onto the PV laminate. This is done so that there is no user access to the DC output of the PV, and to provide easy integration of the inverter to the PV.

Ascension Technology chose to use a modified version of ASE Americas ASE-300-DG/50 PV module. Our choice of this module was based upon three important factors. First, the experience and quality of ASE Americas and their products is excellent. Second, ASE provides the largest power rating in a single module, allowing us to use a larger inverter for the AC Module. And third, the ASE Americas modules are the only UL Class A Fire Rated Modules that exist today.

The ASE PV module is modified to use a special mounting method for quick attachment of the inverter, and is provided as a UL recognized component. The mounting attachment of the inverter is bonded permanently to the rear of the PV module, but also allows quick removal of the inverter to allow for service and swap out of inverters for repair.

The inverter integration is done at ASE's facilities in Billerica, Massachussetts and shipped from there to the customer. At the present time, production capacity is limited by the rate at which inverters may be produced.

Total AC Module production capacity is also 2500 units per year, representing 627.5 kW_{ac} capacity at STC.

Production Failure Rates

The initial pilot production run of 109 units had a final failure, or scrap rate of 0 units. At various points in the production process, if failures were found, they were identified, reworked and ultimately all units passed production tests. Data from the in process failures was recorded and is being used to improve the process. Approximately 20 out of the 109 units required some form of rework to pass production tests. The majority of those failures were due to components being stuffed into the circuit boards incorrectly, e.g. incorrect resistor values, or diodes in backwards, etc…, and were easy to correct.

Product Returns

As of December, 1998, there have been three inverters returned for service from one field installation. This installation was experiencing nuisance tripping. It was determined that the trips were likely due to frequency fluctuations of the utility at that particular site. Factory programable setpoints inside the inverters were modified to reduce sensitivity to frequency fluctuations, the inverters were returned to service and the problem has not recurred. The ability to remove the inverter and ship it back to the factory in this case saved Ascension Technology, the cost of a field service visit. Inverters are now programmed in factory production with the less sensitive frequency fluctuation set point.

There have been zero product returns for reasons of hardware failure of field installed SunSine™300 inverters.

Field Failures

Two of the first installations had problems with inverters partially delaminating from the rear of the module. In both cases, it was identified that the units had been shipped from the factory before the inverter/module adhesive had time to properly cure. Procedures are now in place to prevent product shipment prior to full curing of the adhesive. This problem has not recurred.

PVMaT 4A1 Manufacturing Improvements

At the beginning of this project, Ascension Technology only had two AC Module prototypes. One was located at Sandia National Laboratories for testing and the other at Ascension Technology's offices in Waltham, MA. The design was not offered for commercial sale, and was not suitable for commercial introduction. This project allowed the initial establishment of a production capacity of 2,500 units per year, modification of the design for manufacturability, and enabled commercial introduction and offer for sale of the SunSine™300 AC PV Module.

SunSine™300 Installations

An important part of making the pilot production successful was the commitment by a number of electric utilities to purchasing units for testing. The following utilities participated by purchasing units for evaluation.

SunSine™300 Evaluation Utility Participation
New York Power Authority (NYPA)
Southern Company Services
Arizona Public Service
Central & Southwestern
Delmarva Power & Light
New England Electric System
New York State Electric & Gas
Salt River Project
Long Island Lighting Company
Northern States Power
Northeast Utilities
CSG
AllEnergy
Pacific Gas & Electric
Public Service Company of Colorado
Wisconsin Public Service

In addition to the evaluation of units by the utilities, two of the National Laboratories have units under evaluation as well.

SunSine™300 Evaluation National Lab Participation
National Renewable Energy Laboratory
Sandia National Laboratories

Acknowledgments

Ascension Technology would like to acknowledge those utilities who have been patient with us in waiting for shipments of units from the pilot production run. Your participation in evaluating these units has been and continues to be an important contribution to the success of the SunSine™300 AC Module.

Ascension Technology would also like to thank the U.S. Department of Energy PV Program for their support of this project. Commercialization of the World's First UL Listed AC Photovoltaic Module, would not have been possible without the commitment of the Federal Government to support programs such as PVMaT.

And finally, Ascension Technology would like to thank the Technical Monitoring Team, Ms. Thomas and Mr. Kroposki of the National Renewable Energy Laboratory, and Mr. Bower of Sandia National Laboratories. It was a pleasure working with this team throughout this project and we look forward to continued success in the future.

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13. ABSTRACT *(Maximum 200 words)*

The purpose of this PVMaT subcontract was to establish manufacturing capability and enter commercial production with the SunSine™300 AC Module. This goal was achieved when production began in September 1997, first units were shipped in December 1997, and the pilot production of 109 units was completed in the spring of 1998. As of the completion of this PVMaT project, production capacity is 2500 units per year, which represents 627.5 kW AC @ STC. This report provides the background of the development process that led to a commercial version of the SunSine™300; describes the SunSine™300 product, including theory of operation; provides a summary of all the significant test methods that were applied to prototypes of the product, with a summary of test results; and ends with a summary of the production process and a list of project sponsors who received units for evaluation.

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