Inverter Testing at Sandia National Laboratories*

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Abstract. Inverters are key building blocks of photovoltaic (PV) systems that produce ac power. The balance of systems (BOS) portion of a PV system can account for up to 50% of the system cost, and its reliable operation is essential for a successful PV system. As part of its BOS program, Sandia National Laboratories (SNL) maintains a laboratory wherein accurate electrical measurements of power systems can be made under a variety of conditions. This paper outlines the work that is done in that laboratory.

TESTING ACTIVITIES

Inverter testing at SNL thus far has fallen into one or more of the following three categories.

Benchmark Testing

Tests have been designed and performed to benchmark the performance of inverters. The primary goal of benchmark testing is to provide information on inverter performance over a standardized set of tests. This is important because

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of the variations in the manner in which inverters have been rated and specified by the manufacturers. For example, inverter efficiency is often reported as a single number without regard for load characteristics which affect efficiency significantly. These tests are intended to provide information which is useful to PV system integrators in selecting an inverter for a specific application and in anticipating its performance under a variety of conditions.

Development Testing

The purpose of development testing is to assist inverter manufacturers in their development of a technological innovation or refinement of their product. Consequently, the manufacturers are the primary customers for development test results. This service can be significant because creating, equipping, maintaining, and operating a test facility is, in many cases, prohibitively expensive. Key elements of the facility which can be useful include a variety of loads, dc and ac sources, and diagnostic equipment.

Acceptance Testing

In a few cases, inverters have been tested to verify that their laboratory performance meets government contractual requirements. The customers in this case are the end users of the equipment. Since some of the capabilities of the inverter may be new, acceptance testing has typically followed a preliminary period of development testing. Two examples of acceptance testing are a 250-kVA Kenetech hybrid inverter for the Dangling Rope Marina at Lake Powell, Utah, and a 300-kVA Abacus Controls, Inc. hybrid inverter for the U.S. Navy's Superior Valley installation at China Lake, California.

APPLICATION CATEGORIES

Inverter hardware can be grouped into the following four categories.

Stand-Alone

Inverters operating in a stand-alone mode provide ac power from a dc battery. They range in power capability from hundreds of watts to a few kilowatts. Because their market is relatively substantial, including recreational vehicles, boats, off-grid homes, and any application requiring remote operation of ac equipment, many thousands of these units have been manufactured. Consequently, the technology involved in stand-alone inverters is relatively mature. SNL purchases these inverters for bench-mark testing. Issues of interest include load compatibility, power quality, and safety of operation.

Small Grid-Tied

Grid-tied inverters take dc power either from a battery or directly from a PV array and provide ac power to the utility grid. The only grid-tied inverters that have been produced in quantity have had a capacity of a few kilowatts. Typically, they have been produced in response to projects that are least partially subsidized by a utility and/or by the government. The total number that have been manufactured is certainly less than the number of stand-alone inverters, but still in the hundreds. The technology associated with grid-tied inverters is relatively mature. SNL purchases these inverters for bench-mark testing. Issues of interest are those required to provide confidence on the part of potential utility customers, including power quality, safety of operation, islanding protection, and overall reliability.

Small Hybrid

Small hybrids have evolved from small stand-alone inverters. They typically have single-phase ac outputs with power ratings of a few kilowatts. They can operate in a stand-alone mode but also have the capability to interact with a secondary ac source, such as the utility grid or a backup generator. The secondary source is requested by the inverter controls to recharge the battery and/or to power loads when necessary. Variations in control schemes are possible. The manufacturer typically provides the inverter to SNL for evaluation. Issues of interest include load compatibility, voltage regulation, power quality, site control, and safety.

Large Hybrid

Large hybrid inverters can range in size from tens to hundreds of kilowatts and generally have three-phase outputs. Applications for these units are remote military installations and remote village power. Because only a few have been produced, the technology is still under development. The inverter is normally purchased by the end-user. Testing at SNL assists in the final development and may serve as a partial functional acceptance test prior to a final field acceptance test. Issues include load compatibility, voltage regulation, power quality, site control, and safety. Of these, the most challenging has been the control issue.

SANDIA POWER-CONDITIONING SYSTEMS TEST FACILITY

Data Acquisition System

Sandia maintains a laboratory capable of measuring performance of power-conditioning equipment ranging in size from a few hundred watts to hundreds of kW. Voltages and currents are acquired on both ac and dc sides of the equipment and are analyzed to evaluate key parameters including efficiency, distortion, output regulation, and load compatibility. Data is acquired in both averaging and high-speed waveform-acquisition modes. The data-acquisition system uses a 16-bit, 100 kHz digitizer controlled by a National Instruments Labview program. Data is plotted in Microsoft Excel format. Backup instruments for independent corroboration of data include: oscilloscopes, digital multimeters, dynamic signal analyzers, spectrum analyzers, and audio analyzers. Additional quantities which can be evaluated include conducted and radiated radio-frequency emissions, and audible noise.

Hardware

Loads

- Programmable resistive bank: 150 kW, 480 V, 3-phase
- Programmable inductive bank: 225 kVAR, 480 V, 3-phase
- Manual resistive bank: 360 kW, 480 V, 3-phase
- Nonlinear bank: 50 kVA, 277 V
- Motors: 3-phase to 10 hp, 1-phase to ¾ hp with dynamometer and computer control

AC Sources

- Main power grid: 500 kVA, 480 V
- Separately-derived power grid: 50 kVA, 120/240 V
- Permanent onsite diesel generator: 92.5 kVA, 480 V with remote-start panel
- Temporary generator: wiring and switchgear provision for up to 500-kVA
- ac motor-generator: 150 kVA, 480 V

DC Sources

- Photovoltaic arrays: 30 kW configurable (2 each)
- Photovoltaic simulators: 64 kW and 11 kW
- Power supplies: 350 V, 35 A (3 each) and 55 V, 180 A (2 each)
- dc motor-generator: 115 kW, 700 V

Battery Storage

- 720 kWh bank of 288 cells with 1250 AH capacity, configurable to 576 Vdc in 24-V increments
- 52.8 kWh bank of 24 cells with 1100 AH capacity, configurable to 48 Vdc in 6-V increments

Lightning Simulator

- Voltage and current surge generator: Velonix Model 587

TESTING EXAMPLES

Stand-Alone Example: Trace DR1524 Benchmark Test

The standardized set of tests for evaluation of stand-alone inverters results in a two-page test report. The report associated with the 1.5-kW quasi-sine wave Trace DR1524, is shown in the appendix. Efficiency is plotted for various loads. For all inverters, efficiency is not a single value, but is a function of load type and magnitude. Voltage and frequency regulation and voltage distortion are tabulated for a variety of loads. Regulation is very good, whereas distortion is extremely high due to the quasi-sinusoidal waveform. If battery charging is a capability of the inverter, it is characterized in a table. Overloads are applied and the results are tabulated and compared to the manufacturer's specifications. Copies of the test reports for five different stand-alone inverters are available on Sandia's PV website:
http://www.sandia.gov/Renewable_Energy/photovoltaic/pv.html

Large Hybrid Example: Kenetech Development/Acceptance Test

The standardized set of tests for evaluation of hybrid inverters results in a four-page test report. Tests of the inverter (dc-to-ac) mode of operation are analogous to those for stand-alone inverters. In addition, a series of tests summarizes interactions with the generator. Copies of the test reports for two different large hybrid inverters are available on the web site, one of which is that for the 250-kW Kenetech unit developed for Dangling Rope Marina.

Development testing was especially useful in this case, since this was a new product for Kenetech. Their company had extensive experience with wind-powered, grid-tied applications, but little with PV and none with batteries. As a result, their factory testing concentrated on verifying sub-system functionality. Compromises in their factory testing resulted from the lack of a generator, batteries, PV, or realistic nonlinear loads, all of which SNL was able to provide. Tracking of the maximum-power point was refined and tuned, the battery charge algorithm was updated, and a number of inverter/generator transfer issues were uncovered in a relatively short period of time.

This testing served as the laboratory portion of the contract acceptance tests. The inverter met all specifications; however, the voltage imbalance among phases was significant for severe load imbalances. This is shown in Figure 1. Kenetech was apprised of this result and was confident that by deriving feedback from the load side of the output transformer and changing the control algorithm, the voltage imbalance could be acceptably reduced in future products.

Grid-Tied: Development of Benchmark Test

A test plan for grid-tied inverters has been developed and is available for review at Sandia's PV web site. Parameters of interest include efficiency, distortion, radio-frequency interference, maximum power tracking effectiveness, dc and ac operating ranges, acoustic noise, control features, anti-islanding effectiveness, and restart following utility outage.

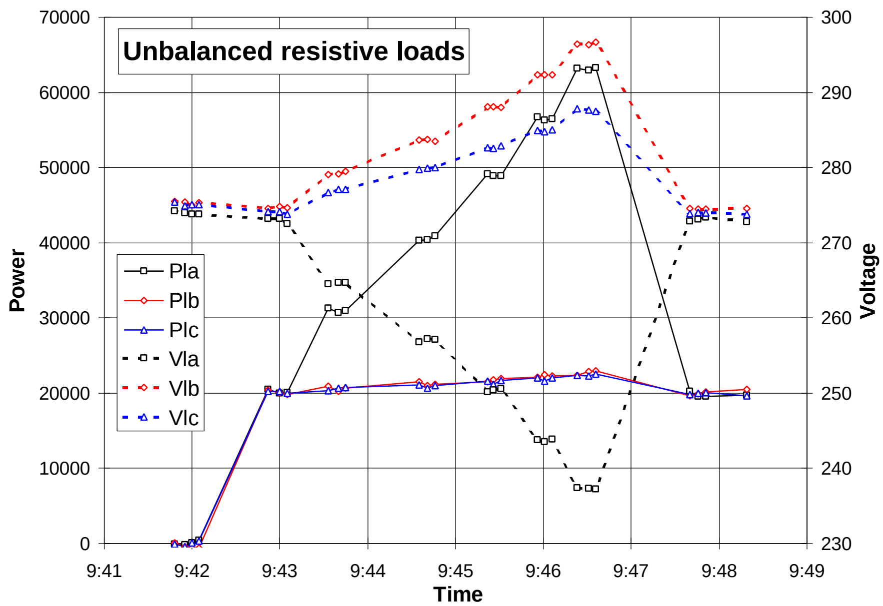


FIGURE 1. Unbalanced voltages resulting from unbalanced loads
(Phase A varied in 10 kW steps with a fixed resistive load on phases B and C)

temperature. Test results will be provided to manufacturers to assist their product development. Another goal of long-term testing is to obtain a statistically significant quantity of data for use in developing IEEE Standard 929, "IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic Systems." This data and IEEE 929 will help utilities assess reliability and any potential negative impact on their systems.

Grid-tied inverters to be characterized fall into two groups, both of which will be treated identically in the test. The first group includes inverters similar to those that have been installed by the Sacramento Municipal Utility District (SMUD), the Environmental Protection Agency (EPA) PV project and others. These include the 4-kW Omnion 2400, 3-kW Pacific Inverter PI-3000, 4-kW Trace 4024, 5-kW Abacus Sunverter, and a 2.2-kW inverter by Sanrex, a Japanese manufacturer. The second group includes module-scale inverters, which are mounted permanently as an integral part of a PV module. The two manufacturers that have developed hardware of this type for the PV Mat initiative are Ascension Technologies and Solar Design Associates, which uses an AES inverter. Module-scale inverters manufactured by Trace Engineering and Evergreen are also planned to be included.

SUMMARY

The goal and future direction for the three types of SNL inverter testing are as follows.

Benchmark testing will:

1. result in a standardized method for evaluating inverters
2. influence government specifications
3. provide useful information to system integrators
4. reassure utilities that PV inverters will not interfere with their operation

Development testing will:
1. support PVMat, SNL R&D in reliability, and inverter manufacturers
2. be coordinated with system requirements to ensure best possible design

Laboratory acceptance testing will:
1. reduce field down time by early detection of problems
2. provide useful information on system performance
3. support users with potentially significant market impact

All SNL testing is under continuous development. Suggestions are actively solicited.

Appendix: Stand-Alone Inverter Test Report of the Trace DR1524 1.5-kW Quasi-Sine-Wave Inverter

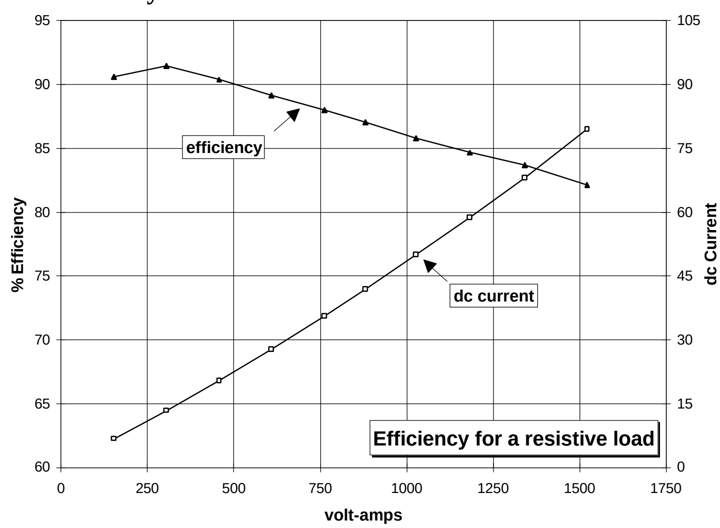
manufacturer's specifications

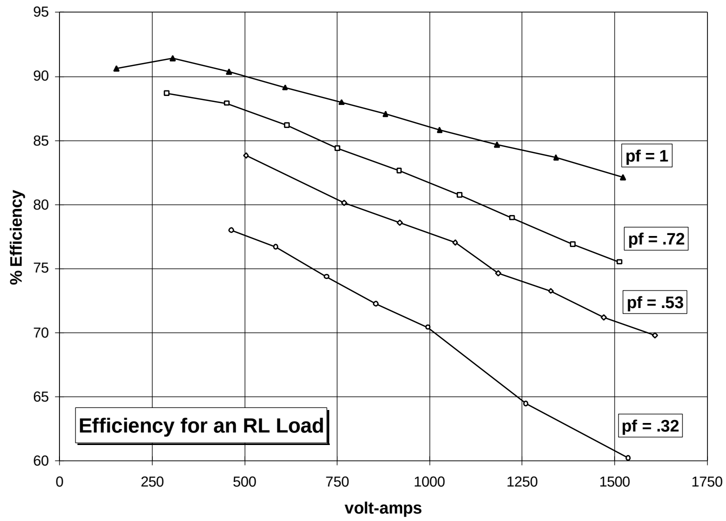
Model Evaluated	DR1524	Output voltage	120 Vac
Rated Power	1500 W	Distortion	N/A
Rated volt-amps	not specified	dc disconnect voltage	22 Vdc
Surge power	4500 W	dc float voltage	N/A
Efficiency	94% (maximum)	Max charge rate	N/A

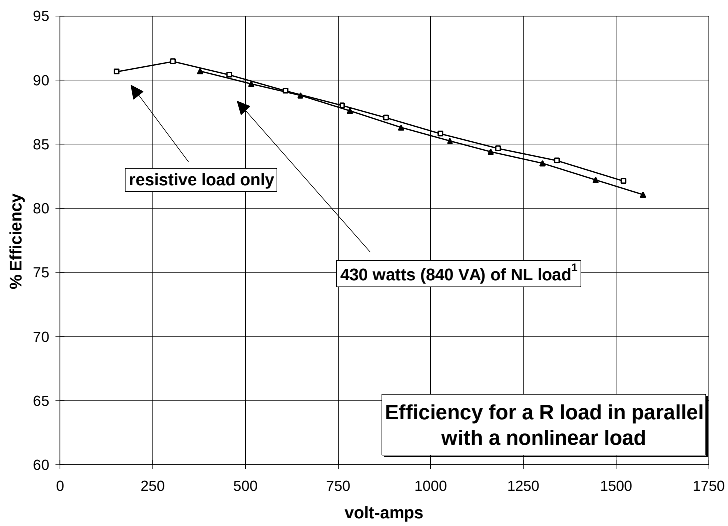
dc evaluation using 200 A-H battery (Trojan T-105)

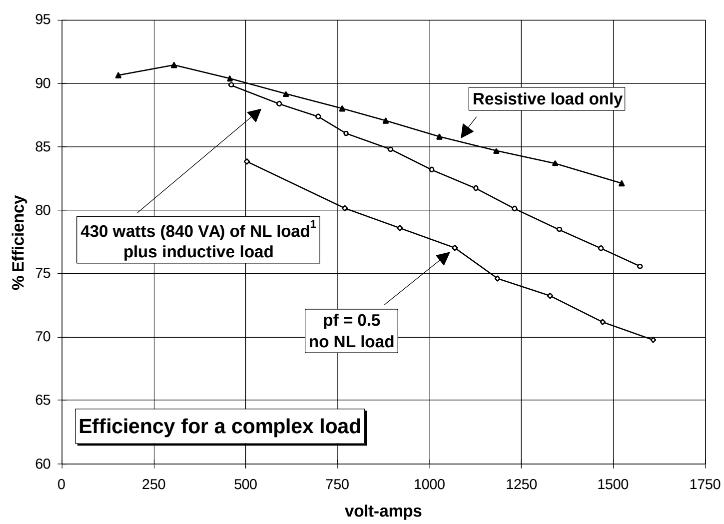
Parameter	Quantity
Inverter Mode	
battery disconnect voltage	21.2 Vdc
Charge Mode	
dc ripple voltage peak (float)	1.1 V
dc ripple current peak (float)	28 A at 2.3A float
battery float voltage	26.6 Vdc
charging efficiency	91% average

efficiency




Efficiency for an RL Load
pf = 1
pf = .72
pf = .53
pf = .32
% Efficiency
volt-amps
95
90
85
80
75
70
65
60
0
250
500
750
1000
1250
1500
1750


Efficiency for a R load in parallel with a nonlinear load
resistive load only
430 watts (840 VA) of NL load1
% Efficiency
volt-amps
95
90
85
80
75
70
65
60
0
250
500
750
1000
1250
1500
1750


Efficiency for a complex load
Resistive load only
430 watts (840 VA) of NL load1
plus inductive load
pf = 0.5
no NL load
% Efficiency
volt-amps
95
90
85
80
75
70
65
60
0
250
500
750
1000
1250
1500
1750

voltage and frequency regulation, and distortion

Note: Regulation is referenced to no-load values of 118.7 Vac and of 60.00 Hz.			
Test Configuration	% voltage regulation	% frequency regulation	% voltage distortion
% full load (PF = 1.0)			
no load	0	0	42
20% full load	2.4	0.0	37
50% full load	3.0	0.0	27
90% full load	2.9	0.0	28
100% full load	2.1	0.0	31
full load reactive			
PF = .5	1.2	0.0	31
PF = .72	1.1	0.0	32
non-linear loads in parallel with R			
NL = 56% of rated VA (VA @ 75%)	3.6	0.0	27
NL = 56% of rated VA (VA @ 100%)	3.5	0.0	33
motor loads			
motor only	[2]	[2]	[2]
motor plus R = 100% full load	[2]	[2]	[2]

inverter overload

Test Configuration	Planned Load Duration	Measured Load Duration	Manufacturer's Specification	Measured Power Level
full load	5 hours	5 hours	1500 W	1550 W
full load + 20%	15 minutes	15 minutes	not specified	1600 W[3]
full load + 50%	1 minute	1 minute	not specified	1690 W[3]
full load + 100%	30 seconds	30 seconds	not specified	1830 W[3]

motor starting

	SNL line motor only	inverter motor only	inverter fully loaded
initial ac voltage (rms)	117	[2]	[2]
voltage sag	9%	[2]	[2]
voltage regulation	1%	[2]	[2]
surge current (peak amps)	85	[2]	[2]
time to steady state (seconds)	0.13	[2]	[2]
steady-state voltage (rms)	117	[2]	[2]
steady-state current (rms)	12	[2]	[2]

Comments

[1] Nonlinear load drew 430 W (840 VA) when connected to grid and 390 W (520 VA) when connected to inverter

[2] inverter would not start ¾-hp motor load

[3] ac output voltage was reduced; target power levels of 1800 W, 2250 W, and 3000 W could not be achieved