Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems

Prepared by

Ward Bower
Sandia National Laboratories
Solar Technologies
Albuquerque, NM 87185-0703
wibower@sandia.gov

Chuck Whitaker
Endecon Engineering
San Ramon, CA
chuckw@endecon.com

William Erdman, Michael Behnke
BEW Engineering, Inc.
San Ramon, CA
bill.erdman@bewengineering.com

Mark Fitzgerald
Institute for Sustainable Technology

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1 Overview

One measure of the maturity of an industry is the extent to which it has adopted standardized test procedures to establish and verify minimum levels of safety, reliability, quality, and performance. The existence of photovoltaic (PV) product listing procedures (UL1703 for PV modules, UL1741 for inverters) has gone a long way in providing consumers and building and electrical inspectors with the necessary assurance regarding safety and installation requirements. Currently, there is no standardized method or testing body for inverter performance. With hundreds of thousands of inverters installed in grid-tied PV systems worldwide, there is clearly a market for these products. The development of standard test procedures and a corresponding certification program that delivers accurate, believable estimates of inverter performance and, ultimately, system performance, is needed to ensure that market claims and customer expectations are being met.

1.1 Objectives

The objective of this document is to provide a test protocol for evaluating and certifying the performance of inverters for grid-connected PV system applications[1]. The test procedures were developed with the assumption that the primary user of the information generated would be a knowledgeable system designer. However, sophisticated end-users will find the basic information of value, and the data lend themselves to being massaged into broader measures of performance. This procedure suggests calculations for several consumer comparison factors, such as weighted efficiency.

Existing tests used for product listing and interface compatibility purposes (e.g. UL 1741) are not repeated in this test protocol.

The test procedures provided in this document are intended to support an equipment certification program. In addition to specifying particular tests, order of performance, and pass fail criteria, as appropriate, such a certification program would also define characteristics of the certifying body; testing laboratory qualifications (accreditation); procedures for requesting, obtaining, and maintaining certification (application form, fees, etc.); manufacturing review and follow-up procedures; dispute resolution

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[1] This document specifies the tests necessary for certification, not the complete certification process.

processes; and confidentiality, conflict of interest, and other issues that define the relationship between equipment manufacturer and equipment certifier. These issues are beyond the scope of this document, though outlined in Annex A.4.

Tests described in this document are classified as needed for "Certification" and will be either "Recommended" or "Required" to indicate the importance of the test results in predicting performance of the inverter and, ultimately, a photovoltaic system. Some tests, such as inverter performance at temperatures above or below those used here, which are currently performed only by the manufacturer and generally used to verify design or operational algorithms, may need more specific procedures or test equipment to satisfy testing requirements.

Considerations taken into account for determining tests that are needed for certification should include the following:

1. The needs for certification (performance verification, industry-wide performance improvements, elimination of misleading claims, manufacturer-specific or model-specific ratings)
2. The type of certification (hardware compatibility, performance or operation of multiple units)
3. The value of further testing for certification
4. The costs of certification
5. The effectiveness of the certification results
6. The required accuracies
7. The applicability of the certification results in various situations
8. The user of the test results.

1.2 Approach and Methodology

The following steps were used to develop the test procedures presented in this document:

1. Survey and list all possible (old and new, domestic and international) types of testing methods and requirements.
2. Tabulate tests in use and determine where they are applicable and where to expand the tests.
3. Formulate a draft protocol based on needs to certify inverter performance.
4. Choose tests that are necessary, repeatable, possible under less than ideal conditions, and economical.
5. Obtain industry/technical /certification expert feedback.

1.3 Scope and Purpose

This document provides guidelines for tests for the certification of grid-connected inverters with or without energy storage. The tests results will provide information not generally found on today's specification sheets, on listing labels or other labels. The guidelines will help to

1. Determine that the inverter functionally meets the design and interconnect requirements.
2. Verify or establish inverter performance when used in conjunction with photovoltaic systems that are properly sized and rated.
3. Verify or establish relevant operational inverter characteristics.

The tests described in this document apply to grid-connected inverters as well as the stand-alone features of inverters that serve dual roles. They may also be adopted for other uses, such as stand-alone only inverters. Tests cover the inverter operation, performance, the photovoltaic array interface, and the ac grid interface. The tests for operation and performance are conducted over a range of temperatures and array characteristics. In addition to inverter performance certification, these tests may also be performed for troubleshooting or to evaluate performance and operation at any point in the life of the inverter.

Tests related to provisions and verification of controls, protection features, and alarms are included to verify operation and to allow expansion of those tests beyond what is required or recommended for certification. Performance tests including efficiency, MPPT accuracy, voltage and current operating windows, array utilization and features such as set points for out of tolerance ac and dc conditions will be performed as recommended or required for certification.

These tests are intended to be supplementary to UL1741 and are not intended to duplicate or conflict with the UL1741 safety, power quality, utility interconnection or thermal requirements.

2 Definitions

The following definitions are pertinent to performance certification of inverters.

2.1 **Data Acquisition System (DAS):** A system that receives data from one or more locations. (from IEEE Std. 100-1996)

2.2 **Disconnect Switch:** A switching device that breaks an electrical circuit. These devices may have ac or dc voltage and current ratings and may or may not be rated for breaking under load. Disconnect switches usually provide a visible break, and may have a locking feature to provide control over the status of the disconnect switch.

2.3 **Efficiency:** The ratio of the usable ac output power to the total dc + ac input power.

2.4 **Electric Power System (EPS):** (from IEEE Std 1547-2003), "Facilities that deliver electric power to a load".

2.5 **Interconnection:** The equipment and procedures necessary to connect an inverter or power generator to the utility grid. IEEE Std. 100-1996 Def: *The physical plant and equipment required to facilitate transfer of electric energy between two or more entities. It can consist of a substation and an associated transmission line and communications facilities or only a simple electric power feeder.*

2.6 **Inverter:** A machine, device, or system that changes direct-current power to alternating-current power. For the purposes of this test procedure, the inverter includes any input conversion (i.e., dc-dc chopper) that is included in the inverter package and any output device (i.e. transformer) that is required for normal operation.

2.7 **Islanding:** Continued operation of a photovoltaic generation facility with local loads after the removal or disconnection of the utility service. This is an unwanted condition that may occur in the rare instance of matched aggregate load and generation within the island.

2.8 **I-V Curve:** A plot of the photovoltaic array current versus voltage characteristic curve. The shape of IV curve is dependent on the PV cell technology, the configuration of the cells and other devices (e.g., bypass diodes) within the array, varying incident solar irradiance intensity and spectral content, and PV cell temperature.

2.9 **Listed Equipment:** Equipment, components or materials included in a list published by an organization acceptable to the authority having jurisdiction and concerned with product evaluation, that maintains periodic inspection of production of listed equipment or materials, and whose listing states either that the equipment or materials meets appropriate standards or has been tested and found suitable for use in a specified manner. (from the National Electrical Code; Article 100.)

2.10 **Maximum Power Point:** The point on the array I-V Curve that yields the greatest output power.

2.11 **Maximum Power Point Tracker (MPPT):** A function included in an inverter or in a separate device, that attempts to operate and maintain a PV array at its "Maximum Power Point."

2.12 **Parallel / Paralleling:** The act of synchronizing two independent power generators (i.e. the utility and a photovoltaic power plant) and connecting or "paralleling" them onto the same buss. In practice, it is used interchangeably with the term interconnection. IEEE 100 Def.: "The process by which a generator is adjusted and connected to run in parallel with another generator or system."

2.13 **Power Conditioning Subsystem (PCS):** The subsystem (Inverter) that converts the dc power from the array subsystem to ac power that is compatible with system requirements. (From 100-1996) See also Inverter.

2.14 **Power Conditioning Unit, PCU:** A device that converts the dc output of a photovoltaic array into utility-compatible ac power. The PCU (Inverter) may include (if so equipped) the array maximum power tracker, protection equipment, transformer, and switchgear. See also Inverter, Power Conditioning Subsystem (PCS), and Static Power Converter (SPC).

2.15 **Power foldback:** An operational function whereby the unit reduces its output power in response to high temperature, excessive input power, or other conditions.

2.16 **Simulated Utility:** an assembly of voltage and frequency test equipment replicating a utility power source. Where appropriate, the actual Area EPS can be used as the Simulated Utility. (From IEEE P1547.1)

2.17 **Static Power Converter:** A device with control, protection, and filtering functions used to interface an electric energy source with an electric power system. Sometimes referred to as inverter, power conditioning subsystem, power conversion system, solid-state converter, or power conditioning unit. (Preceding is derived from 100-1996). The term solid-state inverter is intended to differentiate a solid-state device from a mechanical motor-generator type converter. See Inverter.

2.18 **Standard Reporting Conditions (SRC):** For photovoltaic performance measurements, a fixed set of conditions that constitute the device temperature, the total irradiance, and the reference spectral irradiance distribution to which electrical performance data are translated. (See ASTM Std E 1328)

2.19 **Standard Test Conditions (STC):** A particular set of SRC defined as 1000 W/m^2 irradiance, 25 C cell temperature, and Air Mass 1.5 spectrum (See ASTM Std. E 1328).

2.20 **Supervisory Control and Data Acquisition (SCADA):** Utility equipment used to monitor and control power generation, transmission, and distribution equipment. (IEEE Std 100 Def): *A system operating with coded signals over communication channels so as to provide control of remote equipment (using typically one communication channel per remote station).* The supervisory system may be combined with a data acquisition system, by adding the use of coded signals over communication channels to acquire information about the status of the remote equipment for display or for recording functions.

2.21 **Utilization: (Array Utilization):** The ratio of the energy (or power) that is actually extracted from the module or array to the maximum energy (power) potentially available from the array. Array utilization less than 1.0 is a result of inaccurate Maximum Power Point Tracking

2.22 **Utility:** For this document, the organization having jurisdiction over the interconnection of the photovoltaic system and with whom the owner may enter into an interconnection agreement. This may be a traditional electric utility, a distribution company, or some other organization. IEEE 100 Def: *An organization responsible for the installation, operation, or maintenance of electric supply or communications systems.*

3 Safety Considerations

Standard electrical system safety practices should be strictly adhered to during the evaluation or testing of a grid-interactive inverter for a photovoltaic system.

4 Background and Test Overview

This document is based on the results of surveys of industry participants, installers, and manufacturers and a compilation of available standards for testing photovoltaic inverters. Test protocol and procedures were provided by scientists and engineers associated with Sandia National Laboratories, Endecon Engineering, and the Southwest Technology Development Institute.

The tests and criteria described in Section 5 were chosen to evaluate inverter performance from the output of the photovoltaic array through the inverter to an electric power system. Tests verify compliance with specifications and evaluate the photovoltaic array interface, the inverter operation, the ac interface and the inverter performance in the system. Other than the stated order within a specific test procedure, the tests may be done in any order convenient to the testing agency..

4.1 Inverter Size

Test procedures and criteria are sometimes a function of the size of the system or inverter being tested. For simplicity, three sizes categorized within this document are roughly defined as

Small: 10-kW or less (may provide single- or three-phase output)
Medium: 10-kW to 100-kW (usually three-phase output)
Large: 100-kW and greater (usually three-phase output).

These size specifications are meant to provide general guidelines for testing and not to restrict testing to distinct categories. Unless otherwise stated, tests are not size-dependent.

4.2 Testing Considerations

Determining which of the tests described in this document should be performed for certification will depend on many factors and may vary by jurisdiction until a standardized certification process is agreed upon. Some variations of the tests may be required by the utility. Other tests may be a standard practice of the buyer or installation contractor. Still other tests may be administered to verify a new product or installation procedure. In some cases, certified factory test results (i.e., those performed by the manufacturer) may suffice in lieu of further third-party or owner testing.

Some performance measures can be difficult to interpret because of multiple simultaneous interactions. For example, inverter efficiency changes as the array operating voltage changes, thus the effect of MPPT inaccuracy, which changes the array operating voltage, may be compounded or partially offset.

These tests must be examined in great detail to make sure the tests are practical and economical.

This test protocol for performance certification provides the recommended procedure for each aspect of inspection, test, or calibration. Exact procedures and evaluation criteria may have to be modified based on system size and local requirements, and by referring to the manufacturer's instruction, data sheets, specification, drawings, and other applicable documentation. Further modifications or additional tests may be needed for inverters using multiple PV inputs with independent MPPT functions. One example is determining how a maximum power output limit is affected by multiple MPPT functions.

Some of the performance tests may also be conducted periodically over the life of the PV system to ensure that reliable and expected operation is maintained or to determine when maintenance may be needed.

Performance certification test reports and manuals should normally be retained by the system owner for all major equipment such as custom transformers, switch gear, inverters, drive motors, tracking controllers, instrument transformers, etc. The manufacturer's certified “Test and Calibration” reports for major equipment may eliminate the need for field-testing some of these components.

5 Test Procedures and Criteria

5.1 General Requirements

For convention, power from the inverter to the simulated utility is considered positive and power from the simulated utility to the inverter is considered negative.

For tests requiring stabilized operating temperature, temperatures are considered to be stable when three successive readings taken at not less than 30 minute intervals following an initial 150 minutes of operation indicates no more than 1°C (1.8 °F) variation between any two readings. Shorter durations may be used if it can be demonstrated that the unit has reached thermal stability

5.2 Test Equipment Requirements

Unless otherwise specified, the requirements in this section apply to all test procedures Basic measurement requirements are provided in Table 5-1.

Table 5-1 Basic Measurement Requirements

Parameter True RMS (V,I,P)	Allowable Maximum Uncertainty	Preferred Maximum Uncertainty
DC Voltage*	± 1% of reading	± 0.25% of reading
AC Voltage	± 1% of reading	± 0.25% of reading
DC Current*	± 1% of reading	± 0.5% of reading
AC Current	± 1% of reading	± 0.5% of reading
DC Power*	± 1% of reading	± 0.5% of reading
AC Power**	± 1% of reading	± 0.5% of reading
AC Frequency	± 0.05 Hz	± 0.01 Hz
Temperature	±1°C	±0.5°C
DC Current Ripple	± 5% of reading	± 1% of reading

*Note: "True RMS" measurements must be made for voltage and current. "True RMS" instruments include the contribution of the ac ripple on dc values in the measurement. The ac ripple on the dc line must be taken into account when the magnitude of the current or voltage ripple is >2% of the dc magnitude. Power measurements made through electronic sampling and mathematical integration must take the voltage ripple and current ripple phase difference into account when either magnitude is >2% of the dc magnitude.
**Note: The ac power measurement should include only the usable 60Hz power.

Though some of the wording of this document implies a data acquisition system, any suitable equipment that provides the necessary functionality and accuracy may be used to perform these tests.

Input voltages and currents are measured at the input terminals of the UUT or between the input supply (e.g., PV array) and the connection point of any optional or ancillary equipment external to the UUT. Output voltages and currents are measured at the output terminals of the UUT or at output terminals of the supplied/required external transformer.

Ambient air temperature shall be measured at least 6 inches (15 cm) horizontally away from the enclosure and at the mid-point of the height of the enclosure, and out of the

UUT's convection or forced airflow. Ambient air movement will be minimized to only that necessary to maintain ambient temperature at the specified level. When an environmental chamber is used to control temperature, shrouds or secondary enclosures may be needed to meet this requirement.

Inverter temperature shall be measured at the switching device, or as close as practical.

5.2.1 Inverter DC Input Power Supply Requirements

For efficiency measurements the inverter dc input supply shall meet the following minimum specifications. For this test, the dc input supply does not necessarily have to provide a PV-like I-V curve, such as defined in Appendix A.3, though such a power supply or an appropriately sized PV array may be used. It should meet as a minimum the following requirements:

a. a maximum voltage ripple of 1.0% over the range of expected operation
b. sufficient rated output so that limitations of the power supply do not affect the results (e.g., rated continuous output exceeding 100% of the inverter rated input over the range of inverter input voltage
c. Adjustable output voltage range of at least the inverter's rated input voltage range

When the dc source has little or no surge limitations, external series R/L impedance inserted between the power supply output and inverter input may be necessary to

- limit surges to the inverter
- isolate the power supply output from the inverter input and eliminate unwanted interactions (i.e. the dc supply regulator controlling the operating point of the inverter or visa-versa)
- isolate the power supply output capacitors to limit the change in absolute value of magnitude of the voltage ripple to no less than 90% of measured values using a properly sized PV array.

Resistance, inductance and capacitance shall remain within ±5% of recorded values during the entire test. Ratings of the components shall be at least 150% of the dissipated power, current, and voltage.

The PV array simulator described in Annex A.3 may be used in lieu of a real PV array to provide a current-voltage characteristic curve (I-V curve) representative of a variety of PV technologies, when such characteristics affect the test results.

When an actual PV array is used as the input source, the supply cabling should be large enough to limit voltage drop to less than 2% of the nominal Vdc. The array must be configured to minimize inductive loops and must be protected according to NEC requirements...

5.2.2 Inverter AC Output (Simulated Utility) Power Supply Requirements

For efficiency measurements the ac output power supply (simulated utility) shall meet the following minimum specifications (a combination of an ac power supply and load bank may be used to satisfy this requirement):

a. Maximum THD of 2.5% and not influenced by the output current of the inverter
b. Maximum impedance at 60Hz less than 5 percent of the inverter output impedance where the inverter output impedance is equal to the inverter rated output voltage divided by the inverter rated output current at unity power factor (Inverter Rated Output Power)/(Inverter Output Current at Rated Power) at fundamental frequency. (The impedance may be a series/parallel combination of resistance and inductance so as to present reasonable impedance at all frequencies while limiting losses)
c. Rated power input (sink) of at least 150% of the inverter rated output at 60 Hz
d. Ability to sink full power over the entire operating voltage range of the inverter
e. Adjustable voltage and frequency ranges at least equal to those of the inverter under test and continuously or in increments of at least ±5% of maximum
f. Frequency stability – frequency shall not change by more than ±0.1 Hz during any single test
g. Respond to a step change of ±50% of maximum power without causing more than a 5% change in output voltage
h. Time-constants associated with the reference waveform that are consistent with changes expected in output power associated with these tests
i. Slew rate for voltage of at least 10 Volts/cycle
j. Slew rate for frequency of at least 1 Hz/cycle
k. Ability to withstand instantaneous switching to open circuits at the output

5.3 DC Input Characterization

5.3.1 Maximum Power Point Voltage Tracking Range

This test will determine the voltage range over which the MPPT operates. The test shall be conducted with the actual maximum power point near the center of the dc current operating range specified by the manufacturer. This test may be conducted using a PV array simulator or a PV array. Because the MPP voltage must be adjusted to determine the range of MPPT operation, the PV array may be supplemented with a properly rated voltage-regulated power supply.

5.3.1.1 Test Procedure

This test will consist of operating the inverter on the array or simulator while the value of the MPPT Voltage is varied. Begin the test with V_{MPP} near the center of the specified range. Slowly ramp or step the V_{MPP} upward at a rate of ≤ 5V/minute until the inverter self limits or reacts according to specifications when the limit of the V_{MPP} is exceeded. Record the value. Repeat the test 3 times. Once the upper V_{MPP} limit is determined the first time, subsequent tests may start 15V below the determined limit.

Repeat the above test with downward increments to determine the lower V_{MPP} limit. Outliers (data points more than 3 standard deviations beyond the average) should be investigated and the test repeated.

Record the power level where limits are determined

5.3.1.2 Reported Values

In addition to tabular presentation of the data collected, report the following values:

V_{MPP} upper limit = minimum of the measured values
V_{MPP} lower limit. =maximum of the measured values

5.3.2 Maximum Power Point Current Tracking Range

This test will determine the current range over which the MPPT operates and if the current of the operating point affects the controls or accuracy. The test shall be conducted with the actual maximum power point near the center of the dc voltage operating range specified by the manufacturer. It is anticipated lowering the operating dc current levels will eventually disable the MPPT circuitry and that level shall be recorded.

5.3.2.1 Test Procedure

This test will consist of operating the inverter near the center of its power rating on the array or simulator while the value of the MPPT Current (I_{MPP}) is varied. Begin the test with I_{MPP} near the center of the specified range. Slowly ramp or step the I_{MPP} upward or increment I_{MPP} at a rate of ≤ 0.02 I_{max}/minute until the inverter self limits or reacts according to specifications when the limit of the I_{MPP} is exceeded. Record the value. Repeat the test 3 times. Once the upper I_{MPP} limit is determined the first time, subsequent tests may begin at a current at least 5% below the original limit.

Repeat the above test with downward increments to determine the lower I_{MPP} limit. Outliers (data points more than 3 standard deviations beyond the average) should be investigated and the test repeated.

Record the power level where limits are determined

5.3.2.2 Reported Values

In addition to tabular presentation of the data collected, report the following values:

I_{MPP} upper limit = minimum of the measured values.
I_{MPP} lower limit. = maximum of the measured values.

5.4 Maximum Continuous Output Power

This test will establish the maximum output power level that the unit can maintain for a period of not less than 180 minutes at the unit's rated maximum ambient operating temperature after reaching thermal equilibrium.

In all cases of the following tests, the ac output will be measured on the utility side of any manufacturer-required transformer. If not supplied by the manufacturer, a transformer meeting or exceeding the manufacturer's minimum specifications will be obtained. Test records shall describe any transformers included in the measurements and state whether such transformers are supplied or required by the manufacturer.

Optional or ancillary equipment, including fans, displays, lighted flamingo statues, etc., shall be included in the measurement (that is, the power that the equipment draws will either be added to the input power level or subtracted from the output power level). Such equipment shall be operated at its maximum power level and duty cycle during each measurement. Testing may be repeated without optional equipment. These results must be clearly distinguished as "without optional equipment".

In the case where multiple inverters are designed to share a common transformer, individual inverters will be measured on the inverter side of the transformer. Transformer losses (in Watts or kW) will be measured independently at the various power levels and when multiple inverters are to be connected to a single transformer, the measured loss shall be divided by the minimum number of inverters that are normally connected. The resulting loss fraction will then be used in the efficiency calculation for a single inverter (i.e., the inverter output will be reduced by that amount).

Inverters that provide more than one nominal ac voltage (e.g., 208Vac and 240Vac) shall be tested as though each nominal voltage signified a different model of inverter. Inverters with multiple inputs shall be tested with all inputs activated. Testing may be repeated with fewer inputs active. These results must be presented with the number of inputs active.

Additional testing may be performed at lower temperatures, specified by the manufacturer. These results must be clearly distinguished as "reduced temperature" values.

The input power source must be capable of providing 150% of the maximum input power rating of the UUT over the entire range of UUT input voltages.

This test may be performed simultaneously with the corresponding conditions in Section 5.5 Conversion Efficiency.

Prior to performing the test, the unit shall be stored at 45±5°C (113±9°F) for a minimum of 24 hours. At the beginning of the test, the unit shall be operated at the 100% power level for at least 2.5 hours and until the inverter temperature measurement (on the switching device heat sink) stabilizes.

Table 5-2 Maximum Continuous Output Power Test Conditions

Test	V_{dc}	V_{ac}	Maximum Power
A	V_{nom}	V_{nom}	
B	V_{max}	V_{nom}	
C	V_{min}	V_{nom}	
D	V_{min}	102% V_{min}	
E	V_{max}	98% V_{max}	

Notes:

a. Test done at nominal frequency (50 Hz or 60 Hz) ±0.1Hz.

b. Input voltages and currents are measured at the input terminals of the inverter or between the input supply and the connection point of any optional or ancillary equipment if such equipment is not sourced internal to the UUT. Output voltages and currents are measured at the output terminals of the inverter or at output terminals of the manufacturer supplied/required external transformer. Record the transformer specifications.

c. V_{nom} = For ac, this is the manufacturer specified nominal ac operating voltage. For dc, use the average of V_{min} and V_{max}.

d. V_{min} = Manufacturer specified minimum operating ac or dc voltage. The minimum dc operating voltage may be a function of the ac operating voltage. If so, use the manufacturer's specifications to determine the proper minimum dc voltage for each test.

e. V_{max} = Manufacturer specified maximum ac or dc operating voltage. The maximum dc operating voltage may be a function of the ac operating voltage. If so, use the manufacturer's specifications to determine the proper maximum dc operating voltage for each test. For inverters used with PV, the maximum dc operating voltage should not exceed 80% of the units maximum rated system voltage (maximum allowable array open circuit voltage).

f. 102% of V_{min} and 98% of V_{max} conditions are selected to provide performance at low and high voltages while avoiding tripping the unit because of minor fluctuations in ac line voltage. Tests may need to be performed to verify the actual ac voltage trip settings prior to performing this test (see, for example, Draft IEEE P1547.1)..

5.4.1 Test Procedure

Maintain the UUT in an environment of at least 45°C for a minimum of 24 hours before testing to help ensure that unit is relatively warm at the beginning of the test and that step 2) will bring the unit to a stable operating temperature in a reasonable period of time.

1) Adjust the test environment air temperature to the manufacturer's stated maximum operating temperature ±3°C.
2) Connect the UUT according to the instructions and specifications provided by the manufacturer to the selected input and output power sources.
3) Set all input source parameters to the nominal operating conditions for the UUT.
4) Set (or verify) all UUT parameters to the nominal operating settings.
5) Set the UUT (including the input source as necessary) to provide 100% of its rated output power.
6) Record all applicable settings.
7) Set the UUT to operate at the manufacturer's stated maximum output power level.
8) Set the input source to provide the power level necessary to achieve the desired output power level and at the input voltage defined in Test A in Table 5-2.
9) Set the simulated utility to provide the ac voltage defined in Test A in Table 5-2.
10) Allow the unit to operate for at least 150 minutes and until the heat sink temperature stabilizes
11) After allowing the inverter heat sink temperature to stabilize, measure and record the following values at 5 minute intervals for at least 180 minutes (continuous sampling at higher data rates and 5 minute averages is preferred):
    - Input voltage (dc and ac)
    - Input current (dc and ac)
    - Input power (average dc + ac RMS)
    - Output voltage (ac)
    - Output power (ac)
    - Ambient temperature (°C)
    - Inverter temperature at heat sink (°C).

12) If the unit shuts down, reduce the input power by an amount specified by the manufacturer and begin again. If the test is restarted with no delay, some allowance may be given in the temperature stabilization in Step 10 for heating that has already occurred.
13) Repeat steps 8)-12) for Test Conditions B through E in Table 5-2. If tests are run consecutively, the 150 minute temperature soak in step 10 may be skipped.

5.4.2 Reported Values

In addition to tabular and graphical presentation of the measured data, the unit performance report shall include the following values.

For each Test Condition, calculate and report in Table 5-2

- AC Output Power (minimum of the 5-minute averages or sampled values)

The unit **Maximum Continuous Output Power** will be stated as minimum of the 5 values recorded in Table 5-2.

For temperatures below the maximum ambient operating temperature, values shall be reported as **Reduced Temperature Continuous Output Power (XX °C)**.

5.5 Conversion Efficiency

This evaluation is intended to establish the conversion efficiency of the inverter between the dc source (PV) input and the ac output. The series of tests described in this section will characterize the unit's efficiency as a function of array power, array voltage, utility voltage, and ambient temperature.

In all cases of the following tests, the ac output will be measured on the utility side of any manufacturer-required transformer. If not supplied by the manufacturer, a transformer meeting or exceeding the manufacturer's minimum specifications will be obtained and used. Test records shall describe any transformers included in the measurements and state whether such transformers are supplied or required by the manufacturer.

Optional or ancillary equipment, including fans, displays, lighted flamingo statues, etc., shall be included in the measurement (that is, the power that the equipment draws will either be added to the input power level or subtracted from the output power level). Such equipment shall be operated at its maximum power level and duty cycle during each measurement. Testing may be repeated without optional equipment. These results must be clearly distinguished as "without optional equipment".

In the case where multiple inverters are designed to share a common transformer, individual inverters will be measured on the inverter side of the transformer. Transformer losses (in W or kW) will be measured independently at the various power levels and when multiple inverters are to be connected to a single transformer, the measured loss shall be divided by the minimum number of inverters that are normally connected. The resulting loss fraction will then be used in the efficiency calculation for a single inverter (i.e., the inverter output will be reduced by that amount).

For the following test, the inverter shall be installed in the test fixture according to the manufacturer's instruction in a manner that is representative of typical field installations. To ensure that the unit achieves realistic internal temperatures, all covers and enclosures shall be installed (for example, a secondary enclosure, if required for outdoor installation). Ambient air movement will be minimized to only that necessary to maintain ambient temperature at the specified level. When an environmental chamber is used to control temperature, shrouds or secondary enclosures may be needed to meet this requirement.

Prior to performing the test, the unit shall be stored at 45°C for a minimum of 24 hours. At the beginning of the test, the unit shall be operated at the 100% power level for at least 2.5 hours and until the inverter temperature measurement (on the switching device heat sink) stabilizes.

Care should be taken to record results that occur with the unit in a power foldback mode. When power foldback occurs, mark "Foldback" in the recording sheet and note that foldback has occurred along with the details of the situation.

Table 5-3 lists the matrix of test conditions under which inverters will be evaluated in this test. The empty cells are for recording measured or calculated results.

If possible, the operation of the MPPT should be disabled to reduce the measurement error that would be associated with changes in operating point. If this is not possible, it is important that the monitoring equipment sampling rate must be at least 5 times the MPPT dithering rate and must ensure nearly simultaneous measurement of input and output electrical parameters. Suitable averaging is then used to eliminate the influence of MPPT. It is also important that the simulator response to inverter MPPT operation accurately represent inverter performance when tied to a real PV array.

Inverters that provide more than one nominal ac voltage (e.g., 208 Vac and 240 Vac) shall be tested as though each nominal voltage signified a different model of inverter.

Inverters with multiple inputs shall be tested with all inputs activated. Testing may be repeated with fewer inputs active. These results must be presented with the number of inputs active.

A battery shall be included in the measurement setup if it is included in the normal operation of the inverter and if the dc input source is unable to maintain the desired voltage without excessive ripple. For the performance of this test, the battery shall be maintained at full charge during all measurements (this requirement will necessitate the installation of a separate battery charger to address battery losses during the measurements).

If a PV Array simulator, as described in Annex A3, is used for this test, the simulated PV array is assumed to be at reference conditions, nominal fill factor = 0.68, and with the voltage and power scaled to provide the prescribed conditions (described in Annexes A1 and A2).

Table 5-3 Efficiency Test Conditions

Test	V_{dc}	V_{ac}	Inverter DC Input Power Level						
			100%	75%	50%	30%	20%	10%	5%
A	V_{nom}	V_{nom}							
B	V_{max}	V_{nom}							
C	V_{min}	V_{nom}							
D	V_{min}	102% V_{min}							
E	V_{max}	98% V_{max}							

Notes:

a. Tests done with the MPPT disabled, if possible. Indicate status on data report.
b. Test done at nominal frequency (50 Hz or 60 Hz) ±0.1Hz.
c. Input voltages and currents are measured at the input terminals of the inverter or between the input supply and the connection point of any optional or ancillary equipment if such equipment is not sourced internal to the UUT. Output voltages and currents are measured at the output terminals of the inverter or at output terminals of the manufacturer-supplied/required external transformer. Record the transformer specifications.
d. V_{nom}: For ac, this is the manufacturer specified nominal ac operating voltage. For dc, use the average of V_{min} and V_{max}.
e. V_{min}: Manufacturer-specified minimum operating ac or dc voltage. The minimum dc operating voltage may be a function of the ac operating voltage. If so, use the manufacturer's specifications to determine the proper minimum dc voltage for each test.
f. V_{max}: Manufacturer-specified maximum ac or dc operating voltage. The maximum dc operating voltage may be a function of the ac operating voltage. If so, use the manufacturer's specifications to determine the proper maximum dc operating voltage for each test. For inverters used with PV, the maximum dc operating voltage should not exceed 80% of the units maximum rated system voltage (maximum allowable array open circuit voltage).
g. 102% of V_{min} and 98% of V_{max} conditions are selected to provide performance at low and high voltages while avoiding tripping the unit due to minor fluctuations in ac line voltage. Tests may need to be performed to verify the actual ac voltage trip settings prior to performing this test (see, for example, Draft 6 IEEE P1547.1).
h. If, for any given test, the percentage change in efficiency between the 50% and 100% power levels is less than 2%, the test at 75% may be omitted.
i. The test at 5% of rated power is optional and is provided for consistency with other standard reporting methods (see Table 5-5).
j. Allowable tolerance on input power level is as follows:

Table 5-4 Power Tolerance

Power	Tolerance	Power	Tolerance
5%:	3% – 7%	50%:	45% - 55%
10%:	8% - 10%	75%:	70% - 80%

20%:	18% - 22%	100*%:	95% - 105%
30%:	27.5% - 32.5%		

*Note: When conducting this test, use caution that the inverter does not power limit when the 100% level is exceeded.

5.5.1 Test Procedure

Maintain the UUT in an environment of at least 45°C for a minimum of 24 hours before testing to help ensure that unit is relatively warm at the beginning of the test and that step 2) will bring the unit to a stable operating temperature in a reasonable period of time.

1) Adjust the test environment air temperature to 25°C ±3°C.
2) Adjust the input and output source operating voltages (V_{dc}, and V_{ac}) to nominal values and adjust the input source power to provide 100% of rated output. Allow the unit to operate for at least 150 minutes to bring electronic circuits and components up to a stable operating temperature
3) Adjust the input source operating voltage (V_{dc}) to the Test "A" level shown in Table 5-3
4) Adjust the output source operating voltage (V_{ac}) to the level Test "A" shown in Table 5-3. Adjust the output source frequency to nominal.
5) Adjust the input source power to the first Test "A" level shown (100%) in Table 5-3.
6) After allowing the inverter heat sink temperature to stabilize, measure and record the following values at 30 second intervals for at least 3 minutes (continuous sampling at higher data rates is preferred):
   - Input voltage (dc and ac)
   - Input current (dc and ac)
   - Input power (average dc + ac RMS)
   - Output voltage (ac)
   - Output power (ac)
   - Ambient temperature (°C)
   - Inverter temperature at heat sink.
7) Repeat steps 4)-5) for the remaining Test "A" power levels shown in Table 5-3. If tests are run consecutively, the 150 minute temperature soak in step 10 may be skipped.
8) Repeat steps 2)-6) for Test conditions B through E in Table 5-3. Temperature stabilization may be better facilitated by doing all of the tests at one power level, then changing to the next power level. Either way, tests should be done from highest power level to the lowest.
9) Adjust the ambient temperature to 45 ± 3°C and repeat steps 2)-7).
10) Repeat steps 1) –8) to obtain 5 sets of results for each condition. Outliers (data points more than 3 standard deviations beyond the average) should be documented and those measurement points repeated.

Alternatively, the UUT may be connected to a PV array of suitable voltage and monitored over a clear day with points representing the conditions listed in Table 5-3 extracted from the collected data. PV modules will have to be added to or removed from series strings to provide the prescribed array voltages.

5.5.2 Reported Values

In addition to tabular and graphical presentation of the measured data, the unit performance report shall include the following values.

For each Power Level at each Test Condition, calculate and report

- Average DC Input Power (average of five sampled values)
- Average AC Output Power (average of five sampled values)
- Efficiency = Average AC Output Power/Average DC Input Power. These are the values to be entered into Table 5-3.

The unit **Peak Efficiency** will be stated as the maximum of the 25 averaged efficiency values recorded in Table 5-3.

The unit **Nominal Average Efficiency** will be stated as the average of the nine efficiency values calculated for the 50%, 75%, and 100% input power levels for tests A, B, and C (designated by the shaded area in Table 5-3).

The unit **Weighted Efficiency** is a useful comparative tool for designers and consumers, as systems are installed in a wide range of solar resource regimes. The value of the Weighted Efficiency can be roughly estimated by assigning a percentage of time the inverter resides in a particular range of operation, summing the products of (% time) X (efficiency)/100 to approximate the integral of efficiency X time over the full day. For instance, if the inverter is oversized for the system and the solar resource is marginal, the Weighted Efficiency would be a better predictor of system performance. Weighted Efficiency is calculated using the data taken at the various levels of power according to the equation

$$\eta_{Wtd} = F_1\eta_5 + F_2\eta_{10} + F_3\eta_{20} + F_4\eta_{30} + F_5\eta_{50} + F_6\eta_{75} + F_7\eta_{100}$$

where

η_5, η_{10}, η_{20}, etc. - measured efficiency values at 5%, 10%, 20%, etc. of rated power, recorded in Test A, Table 5-3, above.

F_1, F_2, F_3, etc. - the weighting factors defined in Table 5-5 below:

Table 5-5 Weighting factors for calculating Weighted Efficiency

Factor	Inverter Power Level	Weighting Factor	
		High-Insolation[1]	Low-Insolation[2]
F_1	5%	0.00	0.03
F_2	10%	0.04	0.06
F_3	20%	0.05	0.13
F_4	30%	0.12	0.10
F_5	50%	0.21	0.48
F_6	75%	0.53	0.00
F_7	100%	0.05	0.20

[1] – Based on irradiance and temperature data representative of Southwest US.
[2] – Also known as European Efficiency.

5.6 Maximum Power Point Tracking Accuracy

<*Note: This section does not fully address all of the comments received, and needs to be further reviewed and modified*>.

This evaluation is intended to establish the accuracy of a Maximum Power Point Tracking (MPPT) function when it is attempting to operate a PV array at its maximum power point. This test may be performed on an inverter that incorporates an MPPT, independent MPPT on multiple inputs, or on a separate MPPT device.

A battery shall be included in the measurement setup if it is included in the normal operation of the unit. The battery shall be maintained at approximately 90 percent state of charge during all measurements. This requirement is intended to minimize any influence of the battery voltage or impedance on MPPT performance and may necessitate the use of a separate battery charger or dc loads to maintain the desired battery state of charge.

The performance of the MPPT function often depends on the characteristics of the PV array that the unit is attempting to track. Table 5-6 describes three standard PV array types that will be used for the MPPT tests. Each represents a different MPPT challenge that is strongly related to the array's fill factor. Maximum power voltage on a low fill factor array is a smaller fraction of open circuit voltage than on a high fill factor array. Therefore, the inverter must be able to track over a wider range of voltage if it is also to be used on high fill factor arrays with the same Voc. Also, array power changes more gradually with changes in operating voltage than for medium and high fill factor arrays, conditions that may not be detected by a MPPT controller that uses small fixed step sizes. At the Maximum Power Point on high fill factor arrays, a small change in operating voltage yields a greater change in power than for medium or low fill factor arrays. This characteristic may be troublesome to controllers that are not able to reduce their step size sufficiently.

Table 5-6 PV Array Type Descriptions for MPPT Tests

Array #	Array Type	Nominal Fill Factor* (*FF*)	Temperature Coefficient (β, %/°C)
1	Thin-film	0.55	-0.25
2	Standard Crystalline or Multi-crystalline	0.68	-0.38
3	High-efficiency Crystalline	0.80	-0.50

** - Fill Factor = (Imp*Vmp)/Isc*Voc). Due to model limitations, actual fill factors will be slightly different than listed here.*

For all array types, the following reference conditions are assumed:

Irr_{REF} = Reference plane-of-array irradiance = 1000 W/m^2
T_{REF} = Reference cell temperature = 50 °C

The array or simulator will be adjusted to provide the maximum power point voltage and power specified in the test procedure. MPPT evaluation as described here may require the use of a simulated PV array source device. The characteristics of this device and its calibration are discussed in Annex A.3. That PV simulator shall provide an I-V characteristic response as described by the equations in Annexes A.1 and A.2.

Some of the procedures require that the MPPT operation stabilize before proceeding. Because of the many possible ways of performing the MPPT function, the tester will have to use their best judgment based on the characteristics of the unit under test and the test results to determine when the MPPT has stabilized. It is important to discuss and justify the approach used to determine stabilization.

5.6.1 MPPT Steady State Response Test

For each set of conditions specified in the table below, allow the MPPT device to stabilize[2] at an array operating point. The unit may continue to dither around that point. Record array (simulator) dc voltage and current at a rate of at least 5.0 times the unit's maximum dither rate. Array voltage should be measured at the location where

[2] The "Stabilized Operating Point" on the array for this test should show a dithering voltage profile around the point with <3 dithering steps either up or down before changing direction. Other methods of determining the "Stabilized Operating Point" are allowed. The method used shall be documented.

the simulator or PV array has been characterized. Wiring between that point and the input to the test device should be sufficiently oversized to keep the voltage drop below 0.5% of V_{max}. MPPT accuracy values will be calculated for voltage, current, and power:

$$MPPT\,Accuracy = \frac{Measured}{Expected} \qquad \text{Eqn. 1}$$

where

Expected = the voltage, current, or power of the specified simulator Maximum Power setting

Measured = the measured voltage, current or power at which the MPPT device actually operates the simulator.

If the MPPT device operates the simulator at the expected maximum power voltage, current and power, the MPPT accuracy value will be 1.0. If the device operates the simulator above or below the maximum power point, the value will be in the range, $0 < \text{MPPT accuracy} \le 1.0$.

Table 5-7 lists the matrix of test conditions that will be evaluated in this test. Empty cells are to be filled with measured or calculated results.

Table 5-7 – MPPT Steady State Test Conditions

Test	V_{dc} (V_{REF})	V_{ac}	Array Fill Factor	Inverter DC Input Power Level (P_{REF})				
				10%	25%	50%	75%	100%
A	105% V_{min}	V_{nom}	0.55					
B	V_{nom}	V_{nom}	0.55					
C	95% V_{max}	V_{nom}	0.55					
D	105% V_{min}	V_{nom}	0.68					
E	V_{nom}	V_{nom}	0.68					
F	95% V_{max}	V_{nom}	0.68					
G	105% V_{min}	V_{nom}	0.8					
H	V_{nom}	V_{nom}	0.8					
I	95% V_{max}	V_{nom}	0.8					

Notes:

a. Specified V_{dc} is the intended maximum power point voltage set point for the simulator I-V curve (V_{REF}). The specified input power level defines the simulator maximum power current set point.
b. Testing locations without a suitably sized PV array or simulator may not be able to perform tests at the higher power ranges.
c. $T_{amb} = T_{nom} = 25°C \pm 3°C$. .
d. All voltages and currents are measured at the input or output terminals of the inverter of manufacturer-supplied transformer.
e. V_{min} = Manufacturer specified minimum operating ac or dc voltage.
f. V_{max} = Manufacturer specified maximum operating ac or dc voltage.
g. V_{nom} = Manufacturer specified nominal operating ac or dc voltage or the average of V_{min} and V_{max}.

h. 105% of V_{min} and 95% of V_{max} conditions are selected to provide performance at low and high voltages while avoiding performance discontinuities that might occur when operating at V_{max} or V_{min}.

5.6.1.1 MPPT Test Procedure

1) Set up the array simulator to provide the characteristics specified under V_{dc}, "Array Fill Factor", and the first Input Power Level for Test A in Table 5-7. The output supply voltage and frequency will be set to nominal values.
2) Enable the unit's MPPT function, if necessary
3) Allow the unit to stabilize at or around an operating point. Record all procedures.
4) Measure and record the following:
   1.1 Expected Array Voltage (V_{dc})
   1.2 Expected Array Current (P_{dcdc}/V_{DC})
   1.3 Measured Array Voltage (measured at the simulator terminals or array characterization point).
   1.4 Measured Array Current
   1.5 Measured Array Output Power
   1.6 Time to stabilization
   1.7 Ambient temperature
   1.8 Inverter temperature measured at or near the heat sink
5) Repeat steps 1-4 for the remaining Input Power Levels.
6) Repeat steps 1-5 for Tests B – I in Table 5-7.

5.6.1.2 Reported Values

For each input power level under each test, calculate

a. Average stabilized Measured Array Voltage, Measured Array Current, and Measured Array Power.

b. Voltage Accuracy = $\frac{MeauredArrayVoltage}{ExpectedArrayVoltage}$ Eqn. 2

c. Current Accuracy = $\frac{MeauredArrayCurrent}{ExpectedArrayCurrent}$ Eqn. 3

d. Power Accuracy = $\frac{MeauredArrayPower}{ExpectedArrayPower}$ Eqn. 4

The unit Maximum **MPPT Accuracy** shall be reported as the maximum of the 27 Power Accuracy values calculated for input power levels of 50% and above (designated by the shaded area in Table 5-7). The Minimum MPPT accuracy shall be reported as the minimum of the 27 Power Accuracy values calculated for the same input levels.

5.6.2 MPPT Dynamic Response Test:

The Dynamic Response test is intended to characterize the MPPT response to changing weather (and therefore, array) conditions. The PV array simulator shall be programmed to provide the array I-V curves appropriate for the conditions described in the Slow Ramp, Fast Ramp and Triangle Ramp sections below.

During each ramp, measure and record the following:

a. Expected Array Voltage
b. Expected Array Current
c. Measured Array Voltage (measured at the simulator terminals or array characterization point).
d. Measured Array Current
e. Measured Array Output Power
f. Ambient temperature
g. Inverter temperature at or near the heat sink

Data shall be recorded at a rate of no less than once per 10 seconds for the slow ramp, once per 0.1 seconds for the fast and triangle ramps.

5.6.2.1 Test Procedure - Slow Ramp (Clear day)

The Slow Ramp represents a simplified standard daily variation compressed in time. Figure 5-1 shows representations of the voltage and power profiles for each of the three PV Array types.

The MPPT is allowed to stabilize at the initial conditions of Irradiance = 0 W/m^2 and Temperature = 5 C At time = 0 the simulator begins a continuous ramps from the initial conditions to Irradiance = 1000 W/m^2 and Temperature = 60 °C in 30 minutes. Once reaching those conditions and without pausing, the ramp reverses, returning to 0 W/m^2 and 5 °C in 30 min.

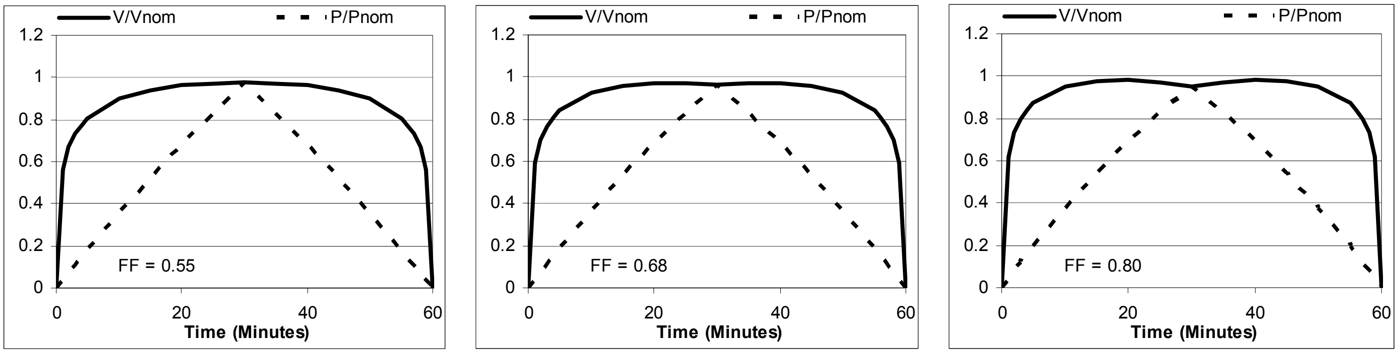

Figure 5-1 Slow Ramp Voltage and Power Curves. V_{REF} is the inverter nominal input voltage and P_{REF} is the inverter rated input power. The three curves represent the three PV technologies listed in Table 5-6.

5.6.2.2 Test Procedure - Fast Ramp (Intermittent cloud cover)

This Ramp is intended to simulate the effects of a cumulous cloud passing in front of the sun. The test determines how quickly the unit responds to a rapid change in array output. Figure 5-2 shows the variation in voltage and power over the test cycle. Note that since there is no change in temperature and the change in voltage with respect to irradiance is nearly identical for all three module types, there is no the differences in curve shape The I-V curve shapes shown in Figure A1-1 will provide the potential for differences in results.

With the unit operating normally and the MPPT operation stabilized, the test begins with an Irradiance change from 100 to 800 W/m^2 in 3 seconds (Temperature = constant = 50 °C). Hold at this condition until MPPT stabilizes. Once the stable operation has been observed, ramp from 800 to 100 W/m^2 in 3 seconds and again hold until MPPT stabilizes. Repeat the procedure to obtain a total of 5 sets of results.

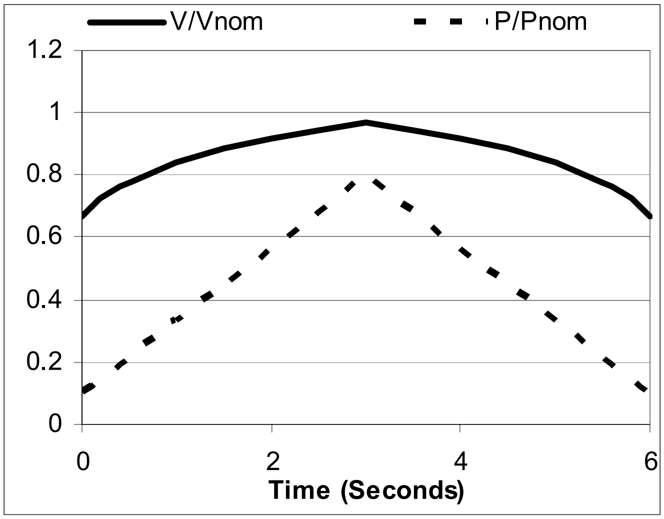

Figure 5-2 Fast Ramp Voltage and Power Curves. Not shown is the dwell time at the 800 W/m² condition and at the beginning and end of the ramps while the MPPT stabilizes.

5.6.2.3 Test Procedure - Triangle Ramp (Partly cloudy day)

The Triangle Ramp shown in Figure 5.3 represents repeated and fast moving clouds and consists of a linear ramp from 100 W/m² to 800 W/m² and back to 200 W/m² in 60 seconds, repeated 60 times.

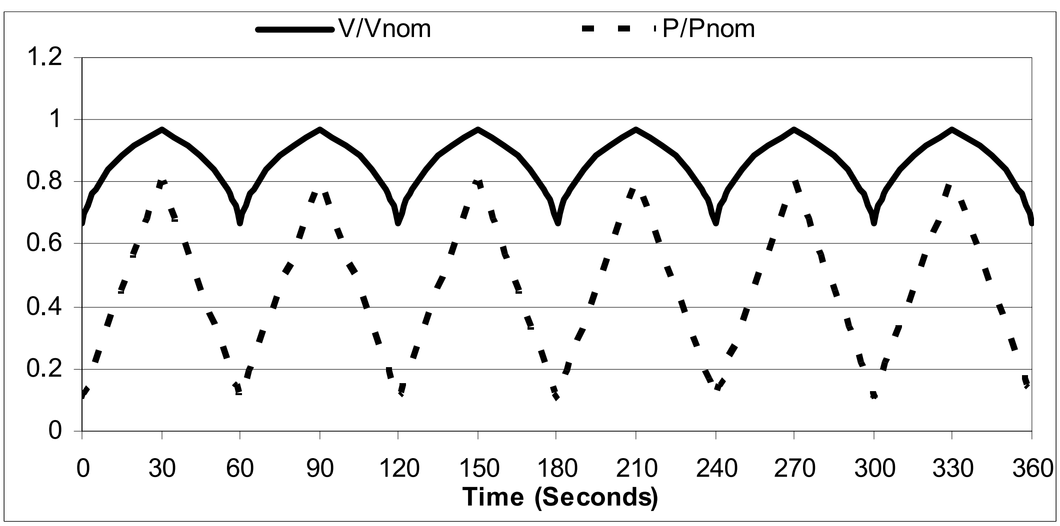

Figure 5-3 Triangle Ramp Voltage and Power Curve. (6 of 60 cycles are shown)

5.6.2.4 Reported Values

For data from the Slow and Triangle Ramp tests, calculate and record the **MPPT utilization** as the ratio of the actual energy obtained from the simulator, to the expected energy for each of the tests. Expected energy is based on the input values to the simulator, the simulator calibration information, and the resulting Maximum Power value at each measurement point, *i*. Actual energy is based on the measured power at each measurement point, *i*. Actual energy is measured from the initiation of the first ramp (ignoring any initial stabilization time) to the completion of the last ramp

$$\text{MPPT Utilization} = \frac{\sum P_{Measured,i}}{\sum P_{MP\ \text{expected},i}} \qquad \text{Eqn. 5}$$

From the Fast Ramp data, for each ascending and descending ramp (10 total), calculate the time from the end of the ramp until MPPT stabilization is achieved. Record the **MPPT stabilization time** as the maximum of the 10 calculated values.

5.7 Tare Losses

This series of tests determines the utility ac power required to operate the unit in standby mode (nighttime Tare losses) as well as the dc input power levels at which the unit starts up and shuts down. To perform this test, it may be necessary to defeat or disable functions (e.g., timers) that might interfere with the results. The tests shall be performed at ambient temperature (25 ± 3 °C)

5.7.1 Test Procedure - Tare Level

1) Begin inverter in standby mode, input dc voltage and power at zero, and simulated utility voltage and frequency at nominal levels.
2) Record the power level to or from the simulated utility
3) Increase the simulated array voltage only (simulated array current and power remains at zero) to the inverter minimum array operating voltage.
4) Record the power level to or from the simulated utility
5) Increase the input voltage only (simulated array current and power remains at zero) to the mid point of the inverter input operating voltage range.
6) Record the power level to or from the simulated utility
7) Increase the input voltage only (simulated array current and power remains at zero) to the maximum of the allowable input voltage range.
8) Record the power level to or from the simulated utility
9) Adjust the input voltage only (simulated array current and power remains at zero) to the mid point of the inverter input operating voltage range.

10) Increase simulated array current level in steps of 0.1% of rated current. Hold at each current level for 5 seconds or otherwise long enough to ensure the unit is not able to successfully start up.
11) Record the input power level just below which the unit successfully transitions from standby to normal operation.
12) Continue to increase the input current level in steps of 0.1% of rated power until the output power rises just above zero (output ≥ 1% of input) and record that value of input current and input power.

5.7.2 Test Procedure - Input Power Level, Startup

1) Begin inverter in standby mode, dc voltage at the nominal value or the midpoint of the allowable input dc voltage range, input dc power at zero, and output ac voltage and frequency at nominal levels.
2) Increase input dc power level at a continuous rate of no more than 0.5%/sec (as a percentage of rated power) or in steps of 0.1% of rated power.
3) Record the input dc power level at which either
4) the unit transitions from standby to normal operation, or
5) the output power goes to zero (output ≥1% of input)
6) If both conditions occur, record both power levels.
7) If the inverter has not yet transitioned to normal operation mode, continue to increase input power until it does so. Record this input power level as Start-up Power.

5.7.3 Test Procedure - Input Power Level, Shutdown

1) Begin with the simulated array and simulated utility configured so that the inverter operates at 10% of nominal input power and at nominal input and output voltages and frequencies.
2) Reduce input power level at a continuous rate of no more than 0.5%/sec (as a percentage of rated power) or in steps of 0.1% of rated power while keeping Vac and frequency constant.
3) Record the input power level at which either
    a. the unit transitions from normal operation to standby/shutdown, or
    b. the output power goes to zero or below (output ≤ 1% of input)
4) If condition “b.” occurs, continue reducing the power until condition “a.” occurs and record both power levels. The Shutdown Power is the maximum of these two values.

5.7.4 Reported Values

Results of these tests shall be reported as:

Tare Level = P_{dc} needed for P_{ac} = 0.
Startup Power = P_{dc} from Test 5.7.2.
Shutdown Power = P_{dc} from Test 5.7.3.

5.8 Power Foldback

5.8.1 Power Foldback with Temperature

This test is used to establish the inverter maximum output power rating over its operating temperature range. This test requires the use of an environmental chamber capable of operating the inverter at the greater of the unit's maximum allowable operating temperature and 50°C. If the inverter is capable of adjusting the PV array operating point to limit the input power, this test should be done with a suitable array simulator.

Notes:

a. Test done at nominal frequency (50 Hz or 60 Hz) ±0.1Hz.
b. Input voltages and currents are measured at the input terminals of the inverter or between the input supply and the connection point of any optional or ancillary equipment if such equipment is not sourced internal to the UUT. Output voltages and currents are measured at the output terminals of the inverter or at output terminals of the mfg supplied/required external transformer. Record the transformer specifications.
c. V_{nom} = For ac, this is the manufacturer specified nominal ac operating voltage. For dc, use the average of V_{min} and V_{max}.
d. V_{min} = Manufacturer specified minimum operating ac or dc voltage. The minimum dc operating voltage may be a function of the ac operating voltage. If so, use the manufacturer's specifications to determine the proper minimum dc voltage for each test.
e. V_{max} = Manufacturer specified maximum ac or dc operating voltage. The maximum dc operating voltage may be a function of the ac operating voltage. If so, use the manufacturer's specifications to determine the proper maximum dc operating voltage for each test. For inverters used with PV, the maximum dc operating voltage should not exceed 80% of the units maximum rated system voltage (maximum allowable array open circuit voltage).
f. $\mathbf{T_{MAX}}$ = Mfg's stated Maximum Operating Ambient Temperature (may be less than 50 °C).
g. All voltage measurement tolerances ±1%.

5.8.1.1 Test Procedure

Maintain the UUT in an environment of at least 45°C for a minimum of 24 hours before testing to help ensure that unit is relatively warm at the beginning of the test and that step 2) will bring the unit to a stable operating temperature in a reasonable period of time.

1) Adjust the test environment air temperature to at least 10 °C below where powerfold back is expected to occur.
2) Adjust the input and output source operating voltages (V_{dc}, and V_{ac}) to nominal values. Adjust the output source to nominal frequency (50 or 60 Hz) ±0.1Hz.

Adjust the input source power to provide 100% of rated output. Allow the unit to operate for at least 150 minutes to bring electronic circuits and components up to a stable operating temperature

3) After allowing the inverter heat sink temperature to stabilize, measure and record the following values at 30 second intervals for at least 3 minutes (continuous sampling at higher data rates is preferred):
   - Input voltage (dc and ac)
   - Input current (dc and ac)
   - Input power (average dc + ac RMS)
   - Output voltage (ac)
   - Output power (ac)
   - Ambient temperature (°C)
   - Inverter temperature at heat sink.
4) If the output power exhibits a decreasing trend at the end of 3 minutes, continue operating and recording 30-second interval data, until output stabilizes.
5) Increase the ambient temperature in 10 ± 3°C steps and repeat steps 3)-4) to a maximum temperature of 50± 3°C.
6) Repeat steps 3) -5) to obtain 5 sets of results for each condition. Outliers (data points more than 3 standard deviations beyond the average) should be documented and those measurement points repeated.

5.8.1.2 Reported Values

In addition to tabular and graphical presentation of the measured data, the unit performance report shall include the following values.

For each temperature step, calculate and report

- Minimum AC Output Power (minimum of sampled values)
- Average AC Output Power (average of sampled values)
- Maximum AC Output Power (maximum of sampled values)

5.8.2 Power Foldback with High Array Output

Power foldback when output power exceeds ratings may be required in order to protect the unit or to meet the requirements reported on listing labels to ensure inverter installations meet the requirements of the National Electrical Code. The power foldback may be an independent operational algorithm contained within the inverter controls or may function simultaneously with temperature foldback that is intended to provide protection to the inverter. The tests described in this section assume the power foldback is an independent function. The temperatures of the electronics and heatsinks shall be monitored during this test to assure temperature foldback is not interfering with the power foldback function. This test may require a temperature chamber to ensure temperature foldback is not occurring. Power foldback must occur in a matter of minutes to meet NEC requirements for continuous ratings of conductors.

5.8.2.1 Test Procedure

Maintain the UUT in an environment of at least 25°C for a minimum of 24 hours before testing to help ensure that unit is relatively warm at the beginning of the test and that step 2) will bring the unit to a stable operating temperature in a reasonable period of time.

1) Adjust the test environment air temperature to 25°C± 3°C.
2) Adjust the input and output source operating voltages (V_{dc}, and V_{ac}) to nominal values. Adjust the output source to nominal frequency (50 or 60 Hz) ±0.1Hz. Adjust the input source power to provide 90% of rated output.
3) Step or ramp the input power from 90% to 150% of rated output power.
4) Measure and record the following values. At least one sample should be taken for every 5% increase in power:
   - Input voltage (dc and ac)
   - Input current (dc and ac)
   - Input power (average dc + ac RMS)
   - Output voltage (ac)
   - Output power (ac)
   - Ambient temperature (°C)
   - Inverter temperature at heat sink.
5) Repeat steps 2) -4) to obtain 5 sets of results. Outliers (data points more than 3 standard deviations beyond the average) should be documented and those measurement points repeated.

Note: Power levels at the output of the inverter should not exceed the UL label rating. If such conditions are observed, record Power Level and Time Above Label Rating.

5.8.2.2 Reported Values

Note in the test report the response of the unit to over power conditions

5.9 Inverter Performance Factor/Inverter Yield

<This section needs to be expanded>

- This test is intended to provide a general characterization of inverter performance encompassing various performance factors (efficiency and MPPT) under a variety of conditions.

- Results presented in kWh/kW (measured ac energy out divided by inverter output power rating)
- Inverter performance will be measured over several a one-day periods, those days having the following characteristics:
  - Day#1: Nominal Conditions: High array fill factor, nominal ambient conditions, nominal array size (provides 100% of rated input power @ PTC) and voltage (provides nominal rated input voltage @PTC). 12 hour day, clear sky conditions
  - Day #2: Same as #1 but high ambient temperature (reduced array output, low array voltage)
  - Day #3: Same as #1 but with partly cloudy conditions (varying array power and maximum power point)
- Other days, may be defined, using different array fill factors, different array sizes (e.g., 33% and 66% of inverter rated input power)
- Test would likely require a PV array simulator, and may allow time compression.
- Use 2:1 time compression and only enough nighttime to allow sufficient cool off.

5.9.1 Test Procedure

1) Program simulator to provide the Day #1 array profile
2) Record inverter input and output parameters
3) Repeat for other Day profiles.

5.9.2 Reported Values

Report the **Inverter Yield** for each of the test Days, calculated as

$$\text{Inverter Yield} = \frac{MeasuredEnergy}{P_{Rated}}, \text{ kWh/kW} \qquad \text{Eqn. 6}$$

6 Glossary of Acronyms

ASTM	American Standards for Testing Materials
DAS	Data Acquisition System
dpf	Displacement Power Factor
EMC	Electromagnetic Compatibility
EPS	Electric Power System
FF	Fill Factor
FCC	Federal Communications Commission
Hz	Hertz (Cycles per second)
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute for Electrical and Electronics Engineers
Imp	PV Array Maximum Power Current
Isc	PV Array Short Circuit Current
MPPT	Maximum Power Point Tracking
NEC	National Electrical Code
OFP	Over Frequency Protection Device or Method
OVP	Over Voltage Protection Device or Method
PCC	Point of Common Coupling
PCS	Power Conversion System
Pf	Power Factor
Pmp	PV Array Maximum Power (Imp * Vmp)
PTC	PVUSA Test Conditions
RMS	Root-mean-square
RFI	Radio Frequency Interference
SCADA	Supervisory Control and Data Acquisition
SPC	Static Power Converter
SRC	Standard Reporting Conditions
STC	Standard Test Conditions
THD	Total Harmonic Distortion
UFP	Under Frequency Protection Device or Method
UL	Underwriters Laboratories, Inc.
UUT	Unit Under Test
UVP	Under Voltage Protection Device or Method
Vmp	PV Array Maximum Power Voltage
Voc	PV Array Open Circuit Voltage
Z	Impedance

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Annexes

A1 Simplified Photovoltaic I-V Curve Model

The following provides a description of a simplified PV I-V curve model. This is the model that shall be used to determine the operating characteristics of the PV Array Simulator described in Annex A3 and used in the MPPT evaluation in Section 5.6.

$$I = I_{SC}\left[1 - C_1\left(e^{\frac{V}{C_2 \cdot V_{OC}}} - 1\right)\right] \qquad \text{Eqn. 7}$$

where

$$C_1 = \left(1 - \frac{I_{MP}}{I_{SC}}\right) \cdot e^{\frac{-V_{MP}}{C_2 \cdot V_{OC}}} \qquad \text{Eqn. 8}$$

$$C_2 = \frac{\frac{V_{MP}}{V_{OV}} - 1}{\ln\left(1 - \frac{I_{MP}}{I_{SC}}\right)} \qquad \text{Eqn. 9}$$

To further define the I-V characteristics, the following relationships are assumed:

$$V_{OC} = \frac{V_{MP}}{\sqrt{FF}} \quad \text{and} \quad I_{SC} = \frac{I_{MP}}{\sqrt{FF}} \qquad \text{Eqn. 10}$$

For the three array types defined in Table 5-6, the following nominal characteristics are assumed:

Table A1.1 – Nominal PV Array Characteristics

Parameter	Array #1	Array #2	Array #3
P_{MP}	1.0	1.0	1.0
V_{MP}	1.0	1.0	1.0
FF	0.55	0.68	0.80
$I_{MP} = P_{MP}/V_{MP}$	1.0	1.0	1.0
V_{OC}	1.35	1.21	1.12
I_{SC}	1.35	1.21	1.12

Based on the nominal characteristics, C1 and C2 were calculated and a series of V and I points were generated. The resulting I-V curves had slightly different characteristics than the initial assumptions. The Maximum Power Point and Fill Factor values in Table A1.2 were obtained from the generated I-V pairs

Table A1.2 – I-V Curve Model Parameters

Parameter	Array #1	Array #2	Array #3
C_1	0.00531	4.88E-05	5.64E-10
C_2	0.191	0.101	0.0470
V_{MP}	0.95	0.95	0.95
I_{MP}	1.07	1.07	1.07
P_{MP}	1.02	1.02	1.02
FF	0.558	0.692	0.815

Sample I-V curves for the three arrays are shown in Figure A1-1.

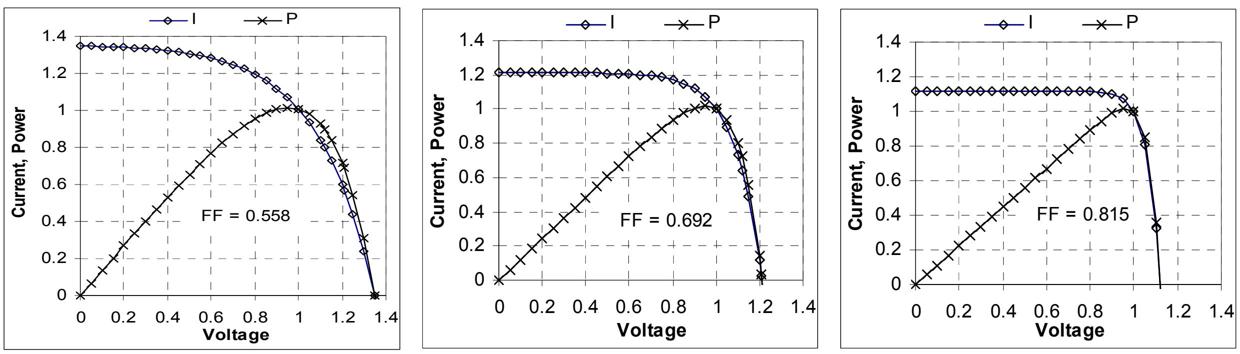

Figure A1-1 Normalized Array I-V Curves

To use, these normalized curves must be scaled to provide the voltage and power specified in the appropriate test conditions. For example, assume an inverter with a nominal rated input power of 4.0 kW and a nominal input voltage of 100V These parameters define the Max Power Point characteristics of the I-V Curve:

V_{MP} = 100V
P_{MP} = 4000W
I_{MP} = P_{MP}/V_{MP} = 40A

To convert the normalized curve to these MPP characteristics, each voltage in the normalized curve would thus be multiplied by a voltage factor, f_V

f_V = 100V/0.95V = 105.26

Similarly, each current value in the normalized curve would be multiplied by the current factor, f_I

f_I = 40A/1.07A = 37.383

Translation of these I-V Curves to other irradiance and temperature conditions is described in Annex A2.

A2 I-V Curve Translation

Annex A1 provides an I-V curve relationship based on reference conditions. The following provides a procedure for .translating the I-V curve based on changes in irradiance and temperature from reference conditions

Reference conditions for all simulated PV arrays are:

Reference Irradiance = Irr_{REF} =1000 W/m^2
Reference Array Temperature =T_{REF} = 50 °C

In the following test procedures, the characteristics of the simulated PV array are provided in terms of array fill factor, Maximum Power Point Voltage and Maximum Power Point Power. A simplified PV Array model defining the relationship between these values and other parameters is provided below:

$$P = P_{REF} \times \frac{Irr}{Irr_{REF}} \times \left(1 + \frac{\beta}{100} \times (T - T_{REF})\right) \quad \text{Eqn. 11}$$

$$V = V_{REF} \times \frac{\ln(Irr)}{\ln(Irr_{REF})} \times \left(1 + \frac{\beta}{100} \times (T - T_{REF})\right) \quad \text{Eqn. 12}$$

$$P = V \times I \quad \text{Eqn. 13}$$

$$FF = \frac{V_{MP} \times I_{MP}}{V_{OC} \times I_{SC}} \quad \text{Eqn. 14}$$

where:
P = Power, Watts
Irr = Irradiance, W/m^2

β = Array temperature Coefficient[3], %/°C
T = Cell temperature, °C
V = Voltage, V
I = Current, A
FF = Fill factor
Subscripts:
  REF = Reference (i.e., at reference or rated conditions)
  MP = Maximum Power
  OC = Open Circuit
  SC = Short Circuit

Values for β are given in Table 5-6

A3 PV Array Simulator Description

For MPPT measurements, the inverter input supply must closely approximate the dynamic response of a PV array. The PV Array Simulator described here may also be used for other tests described in this document. The PV Array simulator shall meet the following minimum requirements:

a. Shall exhibit I-V (current-voltage) characteristics similar to that of a PV array over a range of Voc to 10% of Voc. Must follow a continuous exponential function that goes through a specified open circuit, peak power point, and short circuit point as defined in Annex A1.
b. Shall be capable of simulating I-V curves Fill Factors of between 0.5 and 0.85.
c. Shall be capable of grounded or ungrounded operation.
d. Shall respond to changes in inverter input impedance at rate of at least 99.99 %/s.
e. Shall exhibit a maximum voltage ripple of 0.5% of Voc
f. Shall be capable of providing at least 200% of the rated inverter input
g. Shall be able to supply full power over the entire inverter operating voltage range.

A3.1 PV Array Simulator Calibration

The PV Array Simulator shall be calibrated to ensure that, for a prescribed set of conditions (V_{MP}, P_{MP}, FF, Irr, and T), the actual Maximum Power Point conditions are known within 0.3%.

[3] For simplification, the same coefficient value is used for voltage and power.

The PV Array Simulator shall be calibrated to ensure that all the above stated specifications are met.

A4 Inverter Performance Certification Overview

<In Progress>