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RESIDENTIAL PHOTOVOLTAIC POWER CONDITIONER **MASTER**
SUBSYSTEM TEST PROCEDURES

February 1982

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Prepared for
THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. DE-AC02-76ET20279

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ABSTRACT

The inspections to be made, the conditions for measurement, the variables to be measured and the analyses to be performed in order to characterize the operation of a power-conditioning subsystem (PCS) are described. Of primary concern is the small, utility-interactive PCS in the 2-to 10-kW power range for use in a residential photovoltaic (PV) system feeding a single-phase 120/240-volt line. The procedure is broken down into four main tasks: analysis of the design, tests under nominal conditions, tests under extreme conditions, and accelerated environmental stress tests. The results of these tests will provide an objective assessment of PCS performance under the full range of conditions likely to be encountered in actual applications.

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1.0 INTRODUCTION

1.1 Scope

This document describes the inspections to be made, the conditions for measurement, the variables to be measured and the analyses to be performed in order to characterize the operation of a power-conditioning subsystem (PCS). Of primary concern is the small, utility-interactive PCS in the 2-to 10-kW power range to use in a residential photovoltaic (PV) system feeding a single-phase 120/240-volt line.

Figure 1 is a block diagram depicting the principal components of such a PV system, with a dashed line indicating the elements addressed in this test plan.

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Fig. 1. Typical power-conditioner subsystem in a photovoltaic power system.

1.2 Purpose

The purpose of this document is to provide the means of characterizing PCS performance under a standard set of conditions likely to be encountered in an actual operating environment. The test will be conducted by a neutral party, in a laboratory setting and prior to field installation. The results will highlight modifications to the PCS necessary to its successful functioning in a utility-interactive PV system.

It is important to point out criteria not touched on by this document. It does not offer a qualification standard which a given PCS must pass; however,

selected tests presented here may be useful in preparing such a qualification. It does not assign value, either technically or economically, to the presence or absence of specific features. For example, the operation of a PCS's array-loading control, be it maximum-power-point tracking or constant voltage, will be characterized but the desirability of one control strategy over the other will not. Though it does not directly provide for ranking one PCS relative to another, the results of these tests will probably form the basis for constructing various figures of merit (FOMs) upon which such comparisons can be made. For example, efficiency at various powers and voltages will be measured as part of this test. But for comparing the impact of efficiency curves for two different PCSs, a FOM that uses the data accumulated by these tests will need to be conceived. In the case of comparing efficiency curves, initial indications are that a suitable FOM is one that sums the efficiencies at various power levels, with each efficiency being weighted by the percentage of annual operation at that power level.

1.3 Approach

The document is broken down into four main tasks, with the first task being less conventional than the latter three.

Task One is a thorough examination and analysis of the PCS. The goals of this task are twofold: to uncover areas of the PCS where the design is marginal or unacceptable and to provide predicted values against which some of the measured parameters can be compared. Any significant discrepancies will be used to determine aspects of the PCS that rely more heavily on incidental rather than intentional effects for their operation. For example, a comparator stage appears to be operating in the prototype without oscillations as the comparison point is passed: Is this because an appropriate amount of hysteresis has been intentionally added or is it due to the incidental combination of this particular comparator's characteristics and the input signal's rate of change? Information gained from this task will be useful primarily in assessing the repeatability of the design; that is, in determining the performance implications of factors such as the statistical variations in component

values, systematic variations among "equivalent" components from different manufacturers, and repeatability of construction in areas such as cross talk among circuits, noise on power supply lines, etc. Normally, in product development, this information would be obtained by building and testing many hundreds of units, over a period of several years. The above task has been designed as a cheaper, less time-consuming alternative for providing the required repeatability information.

Tasks Two and Three identify tests and procedures for characterizing PCS technical performance. Tests in Task Two are constructed and conducted under conditions near the center of the range of conditions the PCS will encounter in actual usage. Task Three covers testing in extreme conditions, conditions possible though not probable. Both these tasks include tests for determining the values of parameters, such as efficiency, as well as the effectiveness of control algorithms, such as automatic startup and shutdown. The dc and ac interfaces also receive tests aimed at characterizing the effects of the inverter portion of the PCS on the interface parts.

Task Four presents tests designed to accelerate the stresses normally accumulated over 20-30 years of operation. Since much work remains to be done to establish an effective procedure for estimating from such data the probability of 20-30 year lifetimes for these units, the material in this section is presented in outline form only.

It is evident that the tests, particularly in Tasks One and Four, are not 100% prescriptive. This is intentional. In fact, given the wide variety of approaches, many of them innovative, it is unreasonable to expect that a single, "cookbook" test approach could be meaningful for all the units. This document is really intended to provide a basis from which, when applied, modified and extended by an individual with expertise in power electronics, a fair, thorough test of a PCS will result.

During the evaluation of several PCSs, it will no doubt become apparent that portions of the basic procedure need modification. When a significant number of general modifications have been assembled, this test document should be revised.

All the test results will be recorded in a test log. In some cases the results will be numeric values, in others, narrative; e.g., describing the reaction of the PCS to various abnormal input or output conditions. A report based on the test log will be issued and distributed through the normal channels.

It is envisioned that the material in this document could be applied in any one of several different ways. One relatively straightforward approach would be to perform the general tasks in the order presented below, with individual tests within a task being done in any convenient order. Alternatively, selected tests could be done first with the results forming the basis for a go/no-go decision on further testing. Further, some may prefer to weave the theory of operation section in with the tests while others may prefer to postpone it until all testing is complete.

1.4 Definitions

New or unusual terms used in only one section are defined in that section. Terms not commonly known that are used in more than one section of this document are defined below. Where possible, definitions based on the IEEE dictionary¹ have been used; they are marked with an (*).

1.4.1 Active Power^{*}

At the terminals of entry of a single-phase, two-wire circuit into a delimited region, when the voltage is an alternating voltage and the current is an alternating current, the active power, P, is given by the equation:

$$P_{ac} = \sum_{i=1}^{\infty} E_i I_i \cos(\alpha_i - \beta_i)$$

in which i is the order of the harmonic component of the voltage and current.

1.4.2 Apparent Power^{*}

At the two terminals of entry of a single-phase, two-wire circuit into a delimited region, a scalar equal to the product of the root-mean-square voltage between one terminal of entry and the second terminal of entry, considered as the reference terminal, and the root-mean-square value of the current through the first terminal. Mathematically, the apparent power U is given by the equation:

$$U = EI = \sqrt{\sum_{i=1}^{\infty} E_i^2 \sum_{i=1}^{\infty} I_i^2}$$

in which E and I are the root-mean-square amplitudes of the voltage and current, respectively, E_i and I_i are the root-mean-square amplitudes of the i th harmonic of voltage and the i th harmonic of current, respectively.

1.4.3 Average DC Power

$$\bar{P}_{dc} = \frac{1}{T} \int_0^T E_{dc}(t) I_{dc}(t) dt$$

where

T = period of line frequency

$E_{dc}(t), I_{dc}(t)$ = voltage and current on dc side of PCS

1.4.4 Fundamental Active Power

$$P_{acf} = E_1 I_1 \cos(\alpha_1 - \beta_1)$$

where:

E_1, I_1 = RMS amplitude of fundamental component of ac side voltage and current, respectively.

1.4.5 Fundamental Apparent Power

$$U_f = E_1 I_1$$

1.4.6 Rated Current

The maximum current the PCS can process on a continuous basis under maximum ambient conditions. It may be specified in terms of either the dc or ac side.

1.4.7 Rated Voltage

The maximum dc voltage for which the PCS can process rated current.

2.0 INITIAL EXAMINATION

2.1 Visual Inspection

The PCS will be examined in order to assess the safety of construction and the quality of workmanship.

2.1.1. Safety

The PCS will be inspected for safe design according to the appropriate Underwriters Laboratories (UL) Standard for Safety. In the absence of a final standard, the latest draft standard will be used. Any deficiencies will be noted. An absence of deficiencies will not result in a UL listing. The inspection is intended to be used solely as a guide to highlighting areas needing further work.

2.1.2. Workmanship

Factors affecting the quality of workmanship, such as solder joints component mounting, wire dressing and terminations, will be examined. No standard, analagous to the UL standard used to guide the safety inspection, is available. Thus the areas noted will be those considered deficient by one familiar with good assembly practices.

2.1.3 Installation

The PCS will be checked for its suitability for installation in a residence. Any restrictions, such as indoor versus outdoor mounting, or requirements for dry mounting (e.g., if floor mounted and placed in a basement), will be noted. Compliance with relevant sections of the National Electric Code (NEC) concerning maximum allowable dc input voltage, wire type, adherence to color codes, etc., will also be reported. In lieu of a final NEC code, the latest draft version will be used.

2.2 Operational Familiarization

In this section, the reviewer will be looking for areas in the design which may appear to be functioning normally in the present unit but are not likely to in subsequent units. A key area will be stresses on the power semi-conductors. Other areas will include checking for marginal design aspects or for designs that may be operating on incidental rather than intentional effects.

2.2.1. Theory of Operation

The appropriate sections of the PCS manual, together with the schematics and PCS hardware, will be examined in detail. The reviewer will have several objectives in mind while conducting this process.

One direct goal will be to determine which types of tests are appropriate for a particular PCS. For example: what dc interface control strategy does this PCS use--maximum-power-point tracking or constant-voltage operation?

Another goal will be to assess whether the hardware delivered is wired as shown and operates as described in the PCS manual. Oscilloscope measurements can be made at various important points, to be determined by the reviewer, throughout the unit. These should be checked to see, for example, if the waveforms are clean and the timing margins are sufficient.

A third goal will be to gain sufficient familiarity with the PCS to permit the other two parts of this section, Component Selection and Field Maintainability, to be completed.

Although the topologies upon which a PCS design is based are generally well known, specific implementation may incorporate aspects which the manufacturer feels are proprietary. Such areas must be brought to the attention of the reviewer prior to inspection; information will be used solely for evaluation and will not be released to any third party.

2.2.2. Component Selection

Using the information obtained in Section 2.2.1, specific aspects of the design will be reviewed in an attempt to uncover marginal areas in the design. An example would be the checking of active and passive component ratings to assure that they are adequate for the ranges of electrical and environmental stress under which they will be operated. This review will concentrate on elements in the power train and will include examination of important quantities, such as the estimated junction temperature for semiconductor devices mounted on heat sinks, the voltage and ESR ratings of the input capacitors, etc. The review will also include parametric variations of both element values and temperature ranges. The results of these calculations will be assessed to determine if the accuracy, temperature coefficient, etc., are sufficient for normal inverter operation.

2.2.3. Field Maintainability

The manufacturer's manual will be examined to determine the completeness of a troubleshooting list, and the ease with which parts on the schematic can be located and replaced in the actual hardware, especially the power semiconductor devices. These needs will also be compared against the provisions for field service of the unit. Areas to be covered here include checking existence and determining the suitability of test points and evaluating the ease of exercising control circuits, etc. In performing this part of the evaluation, the intended level of field repair will be taken into account; e.g., is the serviceperson attempting to isolate a faulty component or simply board swap? The need for field-test equipment and/or special test procedures (e.g., floating oscilloscope) will also be noted.

3.0 CHARACTERIZATION UNDER NOMINAL CONDITIONS

3.1 Definition of Nominal Conditions

The conditions put forth below are to be used for all measurements in this section. The conditions were chosen to permit collection of a number of performance measures with the PCS operating under actual, but non-stressful, conditions. The performance measures collected should therefore be representative of the average field performance.

In order to expedite the measurements and assure their uniformity, tests will be conducted with the PCS connected between array and utility simulators. Although the salient features of both the array and the utility will be duplicated by the simulators, some aspects of each will go unduplicated. Thus the final test in this section will be to operate the PCS between an actual array and utility. This will serve both as a final check on PCS performance and as a completeness check on the faithfulness of the simulators.

3.1.1 Array Simulator Voltage

The array simulator will be set to produce a dc voltage that is in the middle of the operating range specified by the manufacturer.

3.1.2 Array Simulator Impedance

Of the several equivalent ways of representing an array electrically, the Norton equivalent, consisting of an ideal current source in parallel with an impedance, will be used here. For a solar array, this impedance will be a function of operating point $Q(V_{dc}, I_{dc})$.

The appropriate impedance has not yet been defined although preliminary work is in progress at MIT Lincoln Laboratory based on the Block IV modules. This impedance will affect the ripple measurements and the adequacy of the PCS input filter. When an appropriate impedance or range of impedances has been determined, the simulator will be set to that value(s).

3.1.3 Array Simulator I-V Curve

The array simulator I-V curve will be comparable to one from a fully functional array, i.e., with no failed cells or modules. To define the shape

of the desired I-V curve at least partially, the fill factor, FF, will be specified. It is defined as follows:

$$FF = \frac{V_{mp}}{V_{oc}} \frac{I_{mp}}{I_{sc}}$$

where:

V_{mp} , I_{mp} = voltage and current at maximum power
 V_{oc} = open-circuit voltage
 I_{sc} = short-circuit current.

The array simulator will be set to have a fill factor of 0.7. Note: There is some overlap of constraints between the specifications in 3.1.2 and 3.1.3.

3.1.4 Utility Simulator Voltage and Frequency

The utility simulator will be set to 120 or 240 V RMS as required by the manufacturer. The frequency will be 60 Hz.

3.1.5 Utility Simulator Impedance

A straightforward way to model the utility is via its Thevinin equivalent; i.e., an ideal voltage source in series with an impedance.

No standard for this impedance has yet been adopted. Initial work has been performed by General Electric² and Lincoln Laboratory³. This impedance will affect the voltage harmonics present on the utility line. When a value or range of values has been chosen, the utility simulator will be set to that value(s).

3.1.6 Environmental Chamber Ambient Temperature

The PCS will be operated in a 20°C ambient with normal convective flow permitted through the unit.

3.1.7 Environmental Chamber Ambient Humidity

The chamber will be operated at 70% RH.

3.2 Parameter Characterization

Included in this section are measurements on variables that provide information on PCS performance based on an input/output point of view and that permit comparative judgments to be made among various PCS approaches.

3.2.1 Active Power Flow

3.2.1.1 Efficiency

Of primary interest is the efficiency of producing active power at the fundamental of the line frequency, η_f . Some PCS approaches produce waveforms whose shape differs significantly from a sine wave. In assessing the impact of these units on a utility, knowledge of the active power at the fundamental and the harmonics of the line frequency is also useful; hence the total efficiency, η_t , will be measured. A useful FOM in the later regard is: $1 - \eta_t / \eta_f$. In general, both efficiencies are a function of dc power level, P_{dc} , and dc voltage level, V_{dc} . The efficiencies will be calculated from measurements of dc average power, $\bar{P}_{dc}$, and the ac fundamental active power, P_{acf} , and the total ac active power, P_{act} , as follows:

$$\eta_f(\bar{P}_{dc}, V_{dc}) = \frac{P_{acf}}{\bar{P}_{dc}}$$

$$\eta_t(\bar{P}_{dc}, V_{dc}) = \frac{P_{ac}}{\bar{P}_{dc}} .$$

Initially, measurements of efficiency will be made at all of the following combinations of $\bar{P}_{dc}$ and V_{dc} :

$\bar{P}_{dc}$ = 1/8 of rated P_{dc}
= 1/4 of rated P_{dc}
= 3/8 of rated P_{dc}
= 1/2 of rated P_{dc}
= 3/4 of rated P_{dc}
= full rated P_{dc}

V_{dc} = lower limit of operational range
= middle of operational range
= upper limit of operational range.

Efficiency data will be plotted versus $\bar{P}_{dc}$ with V_{dc} as the parameter.

Should these measurements reveal regions where the efficiency is changing rapidly, further measurements at intermediate values will be taken.

3.2.1.2 AC Standby Power

The total active power (i.e., ac side) consumed by the inverter with the dc input open circuited will be recorded as P_{acs} .

3.2.1.3 DC Standby Power

The average dc power (i.e., dc side) consumed with the ac output open circuited will be recorded as $\bar{P}_{dcs}$.

3.2.2 Ripple Currents on the DC Side

Although no standard figure has been defined, a common one to use is:

$$R(\bar{I}_{dc}, V_{dc}) = \frac{I_r}{\bar{I}_{dc}}$$

where:

R = relative ripple level
 $\frac{I_r}{\bar{I}_{dc}}$ = peak-to-peak ripple current
= average dc current.

Measurements will be obtained under the same conditions as efficiency and will be plotted in the same manner.

It is expected that the ripple will be dominated by a $2f_{line}$ frequency component; for 60-Hz systems, this would be 120 Hz. A spectrum plot will be generated for PCS systems that result in other dominant harmonics.

3.3.3 Reactive Power Flow

Traditionally, the measure of the effects of reactive power on utility lines has been in terms of power factor. The likelihood of significant levels of harmonic currents in the PCS output complicates the measurement and meaning of reactive power. One could extend the definition of power factor to a general power factor as follows:

$$PF_g = \frac{P_{ac}}{U}.$$

However, this seems premature since the appropriate measures for the effects of harmonic reactive power on a line have not yet been determined. Therefore, fundamental power factor will be used and is defined as follows:

$$PF_f = \frac{P_{acf}}{U_f}.$$

Information on harmonics will be gathered in the general manner described in Section 3.3.4.

Power factor will be measured at the following levels of fundamental active power:

$$\begin{aligned} P_{acf} &= 0 && \text{output} \\ &= 1/8 && \text{of rated maximum output} \\ &= 1/4 && \text{of rated maximum output} \\ &= 3/8 && \text{of rated maximum output} \\ &= 1/2 && \text{of rated maximum output} \\ &= 3/4 && \text{of rated maximum output} \\ &= && \text{rated maximum output.} \end{aligned}$$

In addition, fundamental reactive power will be plotted versus fundamental active power since at low levels of the latter, the absolute level of reactive power is more indicative of effects on the utility than power factor.

3.3.4 Waveform Analysis

The magnitudes of the PCS utility voltage and current, as well as the phase between them at dc and for each harmonic up to 20 times the line frequency, will be measured with the inverter operating first at 1/8 and then at full rated power. These measurements will provide a data base upon which a number of other quantities can be calculated, as the need or usefulness is demonstrated by the utility interface work. The dc and harmonic amplitude normalizations will be with respect to the line frequency amplitude. For

systems utilizing switching regulators, a second spectrum plot will be made starting at the switching frequency, f_s , and showing the percentage of harmonics normalized by the amplitude of f_s through at least the 20th harmonic of f_s . Measurements will be made using a calibrated signal analyzer connected to a voltage tap on the line or to a current transformer on the inverter output.

3.3.5 Ancillary Measurements

In addition to the above measurements, there are several other measures from which additional insight can be gained although they are redundant in the sense that they could be derived from other measurements. One is simply oscilloscope photographs of one cycle of the PCS's input and output current waveforms with the PCS operating at 1/8 and full rated power. Another is the maximum instantaneous percent deviation of the current waveform from a sine wave. Two other useful measures are the maximum volt-seconds and the ampere-seconds of the PCS current waveform normalized by the value of a sine wave. The peak current and voltage are also useful quantities. Finally, the presence of additional zero crossings that may affect the timing of other PCS commutating circuits will be noted.

3.3.6 Electromagnetic Interference

3.3.6.1 PCS as Source

Two types of electromagnetic interference (EMI) measurements will be made: a) conducted on both the array side and the line side of the inverter and b) radiated from the inverter. Signals from the inverter will be tabulated and compared to limitations of FCC Docket 20780.

Conducted signals with frequencies in the range of 150 kHz to 30 MHz will be measured and tabulated on the array-side conductors and the line-side conductors of the PCS. Both line-to-ground and line-to-line measurements will be made on both dc and ac sides. Measurements will be made using a calibrated signal analyzer connected to a voltage tap on the input or output of the PCS.

Radiated signals with frequencies in the range of 150 kHz to 100 Mhz will be measured and tabulated at distances of 3 and 30 meters from the PCS. Measurements will be made using a calibrated signal analyzer connected to an appropriate antenna to pick up the radiated signals.

3.3.6.2 Susceptibility of PCS

The effects of noise from other PCSs, common household appliances and tools (such as drills) and common RF equipment (such as CB radios) will be determined on the PCS under test.

3.3.7 Acoustic Noise

Acoustic noise from the inverter will be measured and tabulated. Measurements will be made using a calibrated noise level measuring set with microphone to pick up the sounds from the inverter.

3.4 Control Characterization

3.4.1 Array Loading Control

Although there is a variety of conceivable control algorithms, there are several measurements that can characterize control performance, independent of the specific algorithm. Three general measurements will be made followed by an algorithm specific measurement.

3.4.1.1 Temperature Coefficient

With the PCS operating under nominal conditions and initially processing 3/4 of rated power at 20°C, the dc operating voltage and current will be recorded at four conditions of ambient temperature: 0°, 10°, 20° and 40°C. The dc operating voltage and current will be plotted versus temperature. Since the PCS control algorithm and the array simulator output will not change, any change in the dc operating point will be due to temperature-dependent elements within the PCS.

3.4.1.2 Transient Response to a Step Change in DC Current

With the PCS operating under nominal conditions, the dc current will be changed in a step-like fashion while recording the dc voltage for a sufficient

period of time following the change such that all transient effects are seen to damp out. This measurement will be done for two step sizes with each step being applied in both directions:

- 5% change in dc current between 0.75 to 0.80 of rated dc current;
- 50% change in dc current between 0.25 to 0.75 of rated dc current.

The smaller step change should be indicative of the system's linear region response (hence the up and down responses should be the same) whereas the larger step is likely to be indicative of the large signal response (up and down step responses no longer necessarily equal).

3.4.1.3 Transient Response to a Step Change in AC Voltage

With the PCS operating under nominal conditions and each of the following dc current levels $1/4$, $1/2$ and $3/4$ of rated, the ac voltage will be changed in a steplike fashion while recording the dc voltage for a sufficient period of time following the change such that all transient effects are seen to damp out. The step change in ac voltage will be from the minimum to the maximum variation permitted by the ANSI Standard C84.1 voltage range B (-13% to $+6\%$ of V_{ac}) for the point of utilization.

3.4.1.4 Algorithm Characterization

The final test in this section is designed to characterize the performance of the specific algorithm used by the PCS. The test will be partitioned depending upon whether the PCS uses an internal or external reference to control the dc operating point.

3.4.1.4.1 Internal Reference

At present, all PCSs using an internal reference use an algorithm that lies at or between the extremes of full-range, maximum-power-point tracking and zero-range, maximum-power-point tracking, i.e., constant voltage. The latter can be characterized simply by determining the range of adjustment of dc voltage. For maximum-power-point tracking, two tests are needed: the range over which the maximum power point will be tracked and the steady-state accuracy of the tracking algorithm, while operating the PCS under nominal conditions and at $3/4$ rated power.

3.4.1.4.2 External Reference

The most common type of external reference is the "pilot" cell approach. PCSs employing this approach will be tested for their response to loss of the reference and for the susceptibility of the PCS to noise pickup on the external reference lines. Any salient features of the external reference, such as temperature coefficient, will also be noted.

3.4.2 Operation Control

In the intended application of the PCS, no functions for normal operation should require outside operator intervention. There are two primary categories of control that will be required on a regular basis. Other control functions will be tested only to determine their operability. These tests will be done with the PCS operating under nominal conditions.

3.4.2.1 Initiation and Termination of Power Conversion

To test automatic startup and shutdown, two conditions will be used. First, the short-circuit current of the array simulator's I-V curve will start to ramp up from zero to the PCS's maximum rated current at a rate of 0.1 A/min^{*}. Startup under these conditions must be established the first time the current passes through the PCS's startup threshold. The measured startup threshold will be noted and compared to the manufacturer's specification. The shutdown threshold will be measured in the same manner except with the current ramping down. The up and down threshold are often made different in order to avoid on/off cycling. Second, the dc current will be applied in a step-like fashion from zero (respectively rated) current to the startup (respectively shutdown) startup threshold current, the latter value being held for 100 minutes. During the application and the duration of these constant currents, any on/off cycling of the PCS will be noted.

3.4.2.2 Interruption of Power Conversion

The response of the PCS control algorithm to interruption of either the dc or ac connection (open circuit; short circuit will be tested in Sections

^{*}Based on data from the Northeast Residential Experiment Station⁴.

4.2.2 and 4.3.2), will be tested by applying all possible combinations, in time sequences of various intervals, of one or both of the following conditions: dc side interrupt, ac side interrupt. The PCS should cease power conversion when either side is interrupted and resume when both sides have been reconnected. Both the time to disconnect and the time to reconnect will be recorded. Also any current surges and voltage spikes on either the dc or ac sides will be noted.

3.4.2.3 Auxiliary Control Operation

Other control functions, as may be provided by the manufacturer, will be exercised and their response noted in the test log.

3.5 Operation with Actual Array

The PCS will be operated between an appropriately configured actual array and a typical impedance utility. A FOM that has been found to be useful as a global measure for characterizing PCS performance is defined as follows:

$$FOM = \frac{E_m}{E_p}$$

where:

E_m = measured PCS energy output (kWh)

E_p = predicted PCS energy output (kWh).

Evaluation of the FOM requires knowledge of the dc power delivered to the PCS $P_{dc}(t)$, and the ac power, $P_{ac}(t)$ from the PCS. Also, the dc operating point voltage and current $Q(V_{dc}(t), I_{dc}(t))$ need to be recorded. From this information, the predicted ac energy from the PCS can be calculated, via:

$$E_p = \int_0^T P_{dc}(t) \eta_t(V_{dc}(t), I_{dc}(t)) dt$$

as well as the measured ac energy:

$$E_m = \int_0^T P_{ac}(t) dt$$

Note that the the above shows total efficiency being used, therefore the ac power used should be the total active power. Alternatively the fundamental efficiency could be used in the calculation of E_p , provided fundamental active power is used in the calculation of E_m .

By taking the limits of integration over the duration of the experiment, including PCS down times, the FOM will show how well the PCS performed compared to how well it could have performed.

This test will serve several functions. First, it will present a chance for the PCS to operate in a "real" environment. Second, it will permit evaluation of performance over a relatively extended period of time, compared with the previous measurements. Third, it will serve as a cross-check on the laboratory tests by exposing the PCS to various combinations of conditions not covered by the laboratory measurements.

4.0 CHARACTERIZATION UNDER EXTREME CONDITIONS

4.1 Definition of Extreme Conditions

In this section the nominal conditions used for Section 2 will again be used but with selected individual variables being extended to create extreme operating conditions. Such conditions are within the bounds of possibility but in the range of limited probability. Operation under combinations of extreme conditions will be tested in Section 4. The PCS must handle all these conditions "gracefully," i.e., application of the extreme condition should cause no damage to the PCS hardware, the residential appliances or the utility service while these conditions exist. Acceptable options for safeguarding the PCS from the extreme condition range from moving the dc operating point, thereby sacrificing some power, to shutting down completely, thereby sacrificing all power. Further, the PCS must return to normal operation following restoration of normal conditions either automatically or via a simple procedure such as pressing a reset button. The response time between application (respectively removal) of the extreme condition and cessation (respectively restoration) of power conversion will be noted. The entries in the test log for each test will be the degree to which the PCS achieved this "graceful" goal.

4.2 Array Side

4.2.1 Array Voltage

The dc input voltage will be varied up and down continuously at a rate of 10 V/min* between zero volts and the lower limit of the operating range, as specified by the manufacturer. The dc voltage will then be varied up and down between the upper end of the operating range and the maximum specified input voltage. Simulations have indicated that an input voltage 1.9 times the NOCT rated maximum power voltage may be encountered. The adequacy of the maximum specified input will be judged against this criterion.

* Data taken at the Northeast Residential Experiment Station⁴ indicates rates as high as 5 V/min are seen in actual practice.

Finally, surge voltage spikes, whose magnitude and duration have yet to be chosen but are expected to be representative of spikes induced by nearby lightning, will be applied to the input. These spikes will be applied when the inverter is both off and on at nominal conditions.

4.2.2 Array Short

In three separate tests, the positive line will be shorted to ground, the negative line will be shorted to ground and the positive and negative lines will be shorted to each other. Each of these short/removal of short conditions will be repeated 10 times.

4.2.3 Array Degraded I-V Curve

Various "glitches" will be placed in the I-V curve typical of an array with one or more failed modules. The performance of the inverter control algorithm will be noted. Of particular concern will be inverters with maximum-power-point trackers: do they find the wrong maximum power point, do they oscillate between two points on the I-V curve, etc?

4.2.4. Array Multiple Interrupt

The dc side will be interrupted with a switch exhibiting multiple, rapid contact breaks or "chatter" in a single opening or closure. Ten each of these "chattering" openings and closings will be performed.

4.3 Utility Side

4.3.1 Utility Voltage

The ac voltage will be varied up and down continuously between zero and the lower limit of the specified line voltage. The ac voltage will then be varied up and down between the upper line voltage and the maximum specified.

Finally, surge voltage spikes such as those described in IEEE Standard #587,1980, which are representative of spikes occurring on utility lines, will be applied. These spikes will be applied when the inverter is both off and on at nominal conditions.

4.3.2 Utility Short

In separate tests, line-to-ground and line-to-line shorts will be applied and removed ten times for each condition. The test setup should be configured such that the short can be applied continuously to the ac side of the PCS, i.e., the fusing or circuit breaker that is protecting the utility simulator should be after the PCS connection. Any overcurrent protection devices on the output of the PCS should, of course, be included.

4.3.3 Utility Frequency

The frequency of the ac line will be varied from 15 to 200 Hz and the range over which the inverter continues to function will be noted. The specified frequency range, which extends far beyond that expected from a utility, was chosen to test the susceptibility of the PCS to locking on a harmonic or subharmonic of the utility.

4.3.4 Utility Multiple Interrupt

The ac side will be interrupted with a switch exhibiting multiple, rapid contact breaks or "chatter" in a single opening or closure. Ten each of these "chattering" openings and closings will be performed.

4.3.5 Utility Matched Load

With the PCS connected to the utility but with an ac load also connected to the PCS output such that net fundamental active power flowing into the utility is zero, the utility connection will be open circuited. The PCS should disconnect under this matched load condition. The time to disconnect and any unusual waveform output prior to disconnection will be noted.

4.4. Ambient Conditions

As a preliminary to the temperature cycling tests of Section 5, the PCS will be subjected to each of the environmental extremes long enough to permit stabilization and to look for any obviously or potentially destructive conditions.

4.4.1 Temperature

For these tests two classes of ambients will be defined. Ambient 1 is intended to approximate the range of temperatures likely to be encountered by PCSs designed for indoor mounting; the temperature extremes will be 0° to 40°C. Ambient 2 is the analogous case for outdoor use; the temperature extremes will be -30°C to +50°C.

4.4.1.1 Maximum Temperature

Under exposure to the appropriate maximum ambient and relative humidity of 70%, the main heat sink and inductor (if applicable) temperatures will be measured. The inverter will be processing maximum power.

4.4.1.2 Minimum Temperature

Under exposure to the appropriate minimum ambient and a relative humidity of 70%, all control functions such as startup, shutdown, etc., will be exercised.

4.4.2 Humidity

Operation will be verified under 100% relative humidity at 20°C.

5.0 ACCELERATED ENVIRONMENTAL STRESS

During these tests, the PCS will be operated at full power under nominal conditions except as superceded below.

5.1 Determination of Hot Spot Locations

5.1.1 Use thermographic camera to survey assembly interior

5.1.2 Locate hidden hot spots not subject to thermal-imaging techniques

5.2 Temperature Sensor Locations

5.2.1 Ambient

5.2.2 Surface of largest thermal mass

5.2.3 Surface of highest expected temperature

5.3.4 Parts likely to limit thermal performance

5.3 Environmental Tests

Specifications are listed in the appropriate section of Table 1.

5.3.1 Low Temperature Test

5.3.1.1 Soak non-operating

5.3.1.2 Low temperature start

5.3.1.3 Operation to stablization

5.3.1.4 Continuous operation for specific time

5.3.2 High Temperature Test

5.3.2.1 Soak non-operating

5.3.2.2 High temperature start

5.3.2.3 Operation to stablization

5.3.2.4 Continuous operation for specific time

TABLE 1.
Suggested Test Limits

	<u>Indoor Use</u>	<u>Outdoor Use</u>
1. Low/High Temperature Test	0°C/40°C	-40°C/ + 60°C
Soak, non-operating	5 days	10 days
Low/high temperature start	x	x
Operate to stablization	x	x
Continuous operation	20 days	40 days
2. Temperature Cycling		
Low temperature soak to stablization, non-operating	0°C	-40°C
Operation at maximum duty cycle	10 hrs.	20 hrs.
Rate of ambient air temperature change	2°C/MIN	10°C/MIN
High temperature stablization	+40°C	+60°C
Operation at max. duty cycle	10 hrs.	20 hrs.
Repeat test sequence	100 times qualification 10 times ea. unit	100 times qualification 10 times ea. unit
3. Humidity	Similar to JPL but @ 0°C to +40°C	Similar to JPL but @ -40° to +60°C
4. Life Test	Operate continuously at room temperature	Operate continuously in outdoor environment

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