SAND2022-12949C

MODELING INVERTERS WITH MULTIPLE INPUTS: TEST PROCEDURE FOR MEASURING EFFICIENCY

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ABSTRACT: Photovoltaic (PV) inverters convert DC power to AC power. Inverters typically employ maximum power point tracking (MPPT) algorithms to maximize power production. Many modern inverters support several independent MPPT inputs to maximize energy production from arrays with different configurations or orientations. There is no consensus test procedure for evaluating the DC-to-AC conversion efficiency for multi-input inverters. Herein, we propose a test procedure based on the open-source System Validation Platform (SVP) software. We apply the procedure to a commercial inverter with six MPPT inputs to demonstrate that the resulting measurements can be used to fit a model that predicts inverter power at all conditions with reasonable accuracy.

Keywords: inverter, experimental methods, modelling

1 INTRODUCTION

Photovoltaic (PV) inverter efficiency is a critical metric for solar procurement as it directly affects power plant production and, therefore, owner or operator income. It also correlates to device lifetime because losses increase internal component temperatures that cause thermal degradation of the components [1]. In 2004, Bower et al. [2] published a procedure for measuring PV inverter efficiency over a range of test conditions. This procedure produced data that was used to fit the PV inverter model in [3]. Test results for many PV inverters are recorded in the California Energy Commission (CEC) Equipment List [4]. The Bower et al. test procedure is also being applied to multi-input PV inverters but only for conditions of equal DC voltage and DC power applied to each input [5].

In this work, we aim to create a conversion efficiency test procedure for multi-input devices that includes a representative collection of power and voltage inputs. None of the previous test protocols consider the multi-input devices, despite many products on the market with this capability. To design and test the protocol, the team used the open-source System Validation Platform (SVP) to autonomously and accurately capture and analyze hundreds of multi-input efficiency measurements. This SVP software platform has been used in the past as a distributed energy resource (DER) management system [6], a tool for PV inverter reliability measurements [7], and extensively as a platform for interoperability [8] and interconnection standard certifications [9], [10]. The advantage of using the SVP to run the experiments is that a larger range of input parameters can be measured in a short period of time.

The data collected by the test procedure can be used to fit extensions of existing PV inverter models in order to accurately model conversion efficiency for PV inverters operating with unbalanced inputs. The method for extending an PV inverter model, and demonstration of model accuracy, are reported in Hansen et al. [5].

The primary contributions of this work are (a) the establishment of the first multi-input conversion efficiency test protocol and (b) open-sourcing the evaluation environment and test script. The remainder of the paper is structured such that Section II discusses the proposed test protocol, Section III describes the test equipment and process, Section VI discusses the experimental results, and Section V presents conclusions.

2 MULTI-INPUT PHOTOVOLTAIC INVERTER TEST PROTOCOL

A PV inverter with several Maximum Power Point Trackers (MPPTs) comprises two functional stages in sequence:

- A DC-to-DC converter on each input, which holds the connected array at the array's maximum power point (MPP) and converts the input DC voltage to a DC bus at a common DC voltage.
- A DC-to-AC inverter stage which produces AC power from the DC power on the DC bus.

Typically, each DC-DC converter controls voltage (and current) from the arrays connected to its input, and the DC-AC inverter controls the DC voltage on the common bus. Fig. 1 illustrates a block diagram of a PV inverter with multiple MPPTs and assigning variables to DC voltage and power on each input and on the bus.

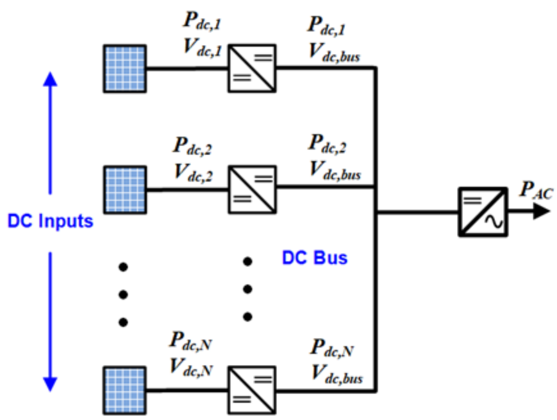

Figure 1. Block Diagram of a Multi-Input PV Inverter.

PV inverters are tested by measuring the DC-to-AC conversion efficiency at select DC input voltages and DC power levels. In the Bower et al. test procedure, multi-input PV inverters are tested by holding each input at the same DC voltage and distributing the total input DC power equally among inputs. In contrast, our test protocol measures PV inverter efficiency over a range of balanced and unbalanced input conditions.

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We implement the test procedure in two test sequences. Test sequence 1 evaluates inputs at 100% or 50% of nameplate power rating with all combinations of minimum or maximum DC voltage on each input, as would be typical in installations with inputs connected to strings of different length and/or shading conditions. Test sequence 2 evaluates the PV inverter with all inputs at one of three DC voltages in combination with several inputs with DC power at 20%, 40%, 60%, or 80%, and the remaining inputs at 100% of nameplate power rating. Test 2 models a system with arrays at different tilt and/or azimuth orientations. Fig. 2 and Fig. 3 present pseudo code for the test sequences. Both test sequences are included in the python script multi_mppt_analysis.py [11].

```
for 1st n inputs derated by 50% in [1…n]
  for all input combinations of {Vmin, Vmax}
    set the I-V curves for the DC inputs
    calculate average MPPT efficiency from m
    measurements
    calculate average conversion efficiency
    from m measurements
  end
end
```

Figure. 2. Algorithm for Test Sequence 1.

```
for MPP voltage in [Vmin, Vnom, Vmax]
  for derating in [0.2, 0.4, 0.6, 0.8]
    for all string combinations in {1.0,
    derating}
      set the I-V curves for the DC inputs
      calculate average MPPT efficiency from
      m measurements
      calculate average conversion
      efficiency from m measurements
    end
  end
end
```

Figure. 3. Algorithm for Test Sequence 2.

3 TEST PROCEDURE

We applied the test protocol to a commercial SMA Tripower Core1 PV inverter, with six MPPT inputs, a power rating of 33 kVA, and an operating voltage of 480 V_{AC}. Test 1 included 448 configurations (2^6 = 64 DC voltage combinations with 0, 1, 2, 3, 4, 5 or 6 derated MPP inputs). Test 2 included 768 configurations (3 voltage levels with 4 derating levels and 64 input combinations). Table I summarizes the PV inverter parameters.

Table I: Description of the inverter parameters

Description	Symbol	Value	Unit
Rated Power	P_{AC}	33	kW
Nominal AC Voltage	V_{AC}	480	VAC
Nominal Frequency	f	60	Hz
Maximum DC Voltage	Vmax	800	VDC
Minimum DC Voltage	Vmin	600	VDC
Nominal DC Voltage	Vnom	720	VDC

Fig. 4 illustrates a block diagram of the laboratory configuration. DC inputs for the inverter were simulated using six channels of a ten-channel AMETEK TerraSAS PV Simulator. Each channel can source DC power that mimics a PV string's IV curve with short-circuit current up to 10 A and open-circuit voltage up to 1000 V_{DC}. AC output from the inverter was exported to the local distribution grid. An Opal-RT real-time grid simulator was used as a convenient calibrated data acquisition system (we did not use its grid simulation capability). The AC current and voltage transducers were calibrated prior to experimentation using a Fluke 5520A High Performance multi-Product Calibrator. The calibration curve for each transducer was calculated by and obtained from a LabView data acquisition system.

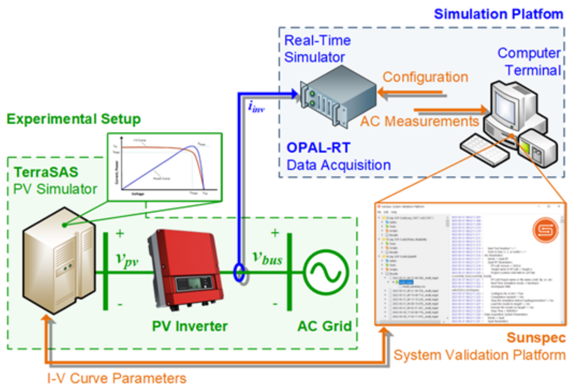


Figure 4. Block Diagram of the Laboratory Testing Configuration.

Experiments were automated by using the open-source System Validation Platform (SVP) software [12] running on a Windows 10 computer connected to the Opal-RT real-time simulator. In the configuration stage, the SVP software set the Opal-RT experiment using the OPAL-RT RT-LAB Python Application Programming Interface (API) and the TerraSAS I-V curves using IEEE 488.2 Standard Commands for Programmable Instrumentation (SCPI) commands over Ethernet.

During the measurement phase, the SVP interacted with the TerraSAS PV Simulator system to record the DC current and voltage. The SVP captured the Opal-RT AC RMS voltage, current, and power for each phase using MATLAB/Simulink.

Test 1 was completed using the SVP in 73 hours, and Test 2 was completed in 10 hours. Test 1 took significantly longer because of the changes in DC voltage. After each change, the PV simulator had to be restarted and the inverter allowed to re-establish maximum power point tracking (MPPT), a process that required several minutes. We first attempted to change the DC voltage without disconnecting the PV simulator, but the inverter would not re-establish MPPT. It may be possible to gradually change DC voltage to avoid disconnecting the PV simulator.

SVP can create a manifest of results within the script log, measurement data files, and a results summary. In each test sequence and at each configuration, 50 measurements were recorded of total AC power (sum over 3 phases), DC power at each input, and other quantities (complete files at [11]). Values of AC power, total DC power and DC power on each input were screened to discard values outside of 150% of the inter-quartile range (75th – 25th percentile). In addition, we noted three instances in Test 2 where the mean DC power on one or more inputs differed by more than 2% from the target power; we discarded these measurements. We surmise that the drift away from target occurs when the inverter MPPT algorithm steers the PV simulator away from the maximum power point on its simulated I-V curve. After filtering, the mean of remaining values is recorded and used to calculate efficiency (total AC power / total DC power) and to fit an inverter efficiency model [5]. Python scripts to perform data filtering, model fitting and analysis are published at [11].

4 RESULTS

Fig. 5 displays the standard deviation of efficiency values for the 768 configurations comprising Test 2. Efficiency is consistently measured within 0.1% (one standard deviation). Full datasets and analysis scripts are available at the GitHub repository [11].

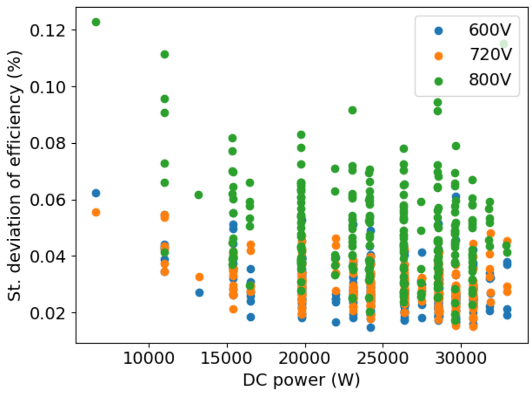


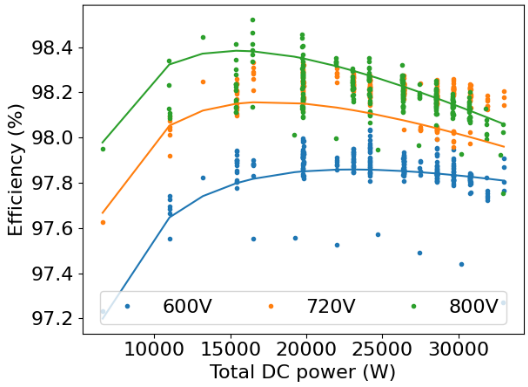
Figure 5. Variation in measured efficiency for Test 2.

Results from Test 1 and Test 2 are combined to form a data set suitable for fitting and validating models to predict inverter efficiency at all operating conditions. Hansen *et al.* [5] describe an extension of the Sandia inverter model [3] for multi-input devices. Here, we follow the current practice of the California Energy Commission (CEC) and fit the model to the "equal power" subset of test data. This subset comprises configurations where the target power is equal for each input as specified by the test procedure of Bower *et al.* [2]. The remaining data are used for validating the model predictions.

Fig. 6 illustrates measured and predicted efficiency and error in predicted AC power. The results demonstrate that the proposed model is generally unbiased with prediction accuracy between ±0.5% (Fig. 6b). Prediction error increases with AC power.

Fig. 6a compares modeled and measured efficiency for the "equal voltage" subset of data (configurations with the same V_{DC} on each input). Restricting the plot to this subset allows for comparing measured and modeled efficiency by voltage level. Fig. 6a shows variance in efficiency at each level of DC power and DC voltage that does not correlate with the DC power level nor with any specific MPPT input ([5], Fig. 4). For unknown reasons, among the 600 V_{DC} results, several configurations from Test sequence 1 show markedly lower mean efficiency than the rest of the data sample.

(a)



(b)

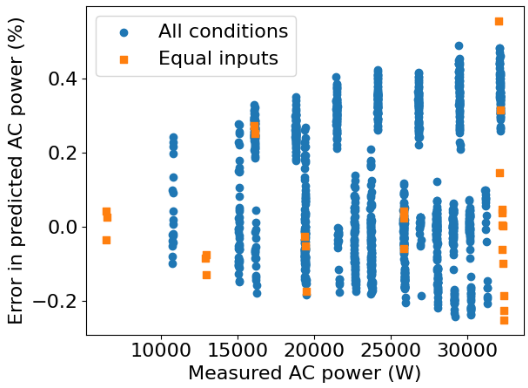


Figure 6. Experimental results: (a) measured (dots) and modeled (lines) efficiency; (b) error in modeled AC power. In (b), "Equal inputs" are points used for model fitting.

5 CONCLUSIONS

In solar installations with multiple arrays configured with different orientations, module types, or topologies, multi-input solar inverters are often used to maximize energy production. Currently a test procedure designed for single-input inverters is being used to measure efficiency of multi-input inverters, and data from these measurements are used to fit efficiency models. This work describes a procedure to evaluate multi-input inverters with different combinations of DC voltage and/or power on the PV inverter's inputs. The automated test procedure captured hundreds of efficiency measurements. Analysis shows that the results of this procedure can be used to parameterize models to predict inverter AC power. However, the measurements require careful filtering to exclude values that may be erroneous, or that indicate that the test equipment was not operating as intended.

6 ACKNOWLEDGEMENTS

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

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