PV Array Simulator Development and Validation

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ABSTRACT

The ability to harvest all available energy from a photovoltaic (PV) array is essential if new system developments are to meet levelized cost of energy targets and achieve grid parity with conventional centralized utility power. Therefore, exercising maximum power point tracking (MPPT) algorithms, dynamic irradiance condition operation and startup and shutdown routines and evaluating inverter performance with various PV module fill-factor characteristics must be performed with a repeatable, reliable PV source.. Sandia National Laboratories is collaborating with Ametek Programmable Power to develop and demonstrate a multi-port TerraSAS PV array simulator.

INTRODUCTION

The simulator will replicate challenging PV module profiles, enabling the evaluation of inverter performance through analyses of the parameters listed above. Energy harvest algorithms have traditionally implemented methods that successfully utilize available energy. However, the quantification of energy capture has always been difficult to conduct, specifically when characterizing the inverter performance under non-reproducible dynamic irradiance conditions. Theoretical models of the MPPT algorithms can simulate capture effectiveness, but full validation requires a DC source with representative field effects. The DC source being developed by Ametek and validated by Sandia is a fully integrated system that can simulate an IV curve from the Solar Advisor Model (SAM) module data base. The PV simulator allows the user to change the fill factor by programming the maximum power point voltage and current parameters and the open circuit voltage and short circuit current. The integrated PV simulator can incorporate captured irradiance and module temperature data files for playback, and scripted profiles can be generated to validate new emerging hardware embedded with existing and evolving MPPT algorithms. Since the simulator has multiple independent outputs, it also has the flexibility to evaluate an inverter with multiple MPPT DC inputs.. The flexibility of the PV simulator enables the validation of the inverter's capability to handle vastly different array configurations.

AMETEK PV SIMULATOR

The PV simulator is a rack-mounted control computer with control software and PV simulation engines. The configuration evaluated for this paper has four programmable DC power supplies that are controlled by the PV simulation engines. Each of the power supplies is a high-speed switching power supply that utilizes power MOSFET technology to minimize the output capacitor and inductor, which typically limits the performance of conventional power supplies. The PV simulator is an integrated system that can simulate an IV curve with programmable parameters that are essential in developing a representative model of today's PV modules.

These parameters are:

- open circuit voltage (Voc),
- short circuit current (Isc),
- maximum power voltage (Vmp)
- maximum power current (Imp)

An array temperature coefficient can be implemented to best replicate module and array characteristics and replicate the performance of the simulated array configuration. The IV curves are produced utilizing the following formula:

Io as a function of Vo:
Io=Isc*(1-C1(exp*(V/(C2 x Voc))-1*Eeff
C1=(1-(Imp/Isc))*(exp(-Vmp/(C2 x Voc)))
C2=((Vmp/Voc)-1)/(In(1-Imp/Isc))
Where:
Eeff=Ginc/Gstc,
Gstc=1000 w/m^2 (standard test conditions)
Ginc=Incident irradiance (Actual Irradiance)

The PV simulator has the flexibility to configure the amount of series/parallel combination of modules needed to meet the operating voltages and power levels required to operate the wide variety of inverters and battery charge controllers. The system software also allows the user to select the module characteristics from the SAM database or change the module fill factor by changing the parameters listed

above. This can be used to simulate different solar cell characteristics, and multiple module characteristics can be combined to produce multiple maximum power points on the IV curve that can challenge any MPPT algorithm. Figure 1 shows the combination of hardware and software components that allows the PV simulator to replicate a variety of photovoltaic technologies and conditions that thoroughly challenge most inverters and charge controllers.

Fig. 1: Rack-mounted AMETEK PV simulator.

The user can program the following parameters: irradiance level; temperature value; temperature coefficient; and simulation time to ramp the voltage, temperature or irradiance level. Figure 2 shows an example of three of the four outputs being used to provide power to the device under test. For this configuration, each of the outputs has two parallel strings with each string containing six modules. Each output is operating at standard test conditions with irradiance set to 1000 w/m^2 and module temperature set to 25°C. The aggregate of the three outputs is shown as the bottom IV curve plot. This plot indicates that all of the outputs are closely matched, since the combined IV curve is smooth and without multiple maximum power points.

Individually configurable outputs allow for various module configurations to be realized. One configuration will be to simulate either different module technologies being utilized for each of the strings or different degradation or performing conditions for each of the strings. Figure 3 shows the output of the simulator with these conditions implemented. It can be demonstrated under these conditions that the IV curve characteristics from the aggregated string combination have multiple maximum

power points and this condition would present challenging performance conditions for most MPPT algorithms. The severity and number of maximum power points will be determined by individual installations and the health of the installation.
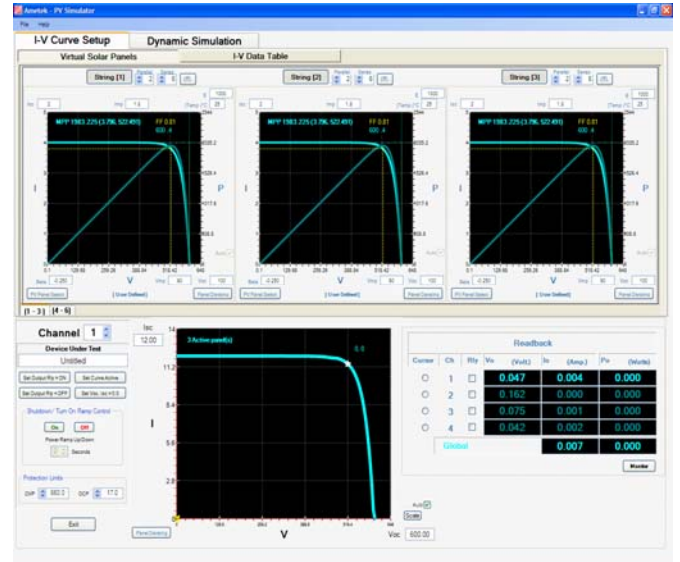

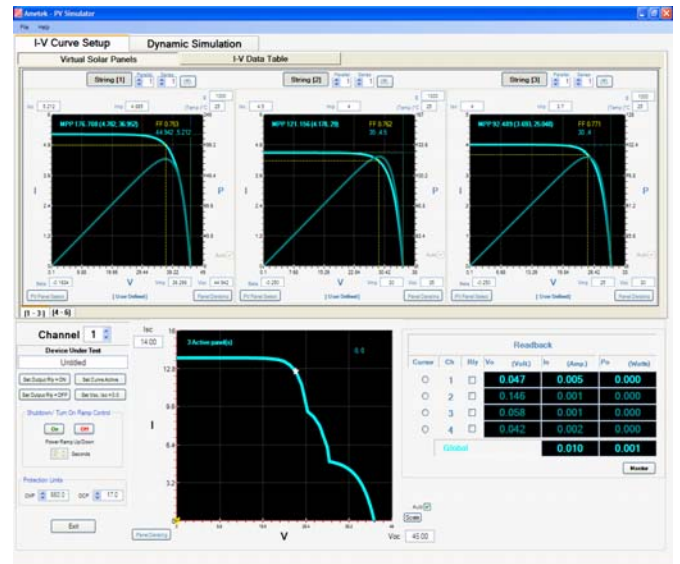**Fig. 2: Similar multi-string configuration characteristics**

Fig. 3: Dissimilar multi-array configuration characteristics

TEST CONFIGURATION

Laboratory evaluations of utility-interconnected PV inverters at Sandia National Laboratories' Distributed Energy Technologies Laboratory (DETL) are typically conducted using c-Si module technologies as the DC source for the device under test and the utility as the AC source. A 50kW$_{STC}$ Solar World SW175 module array can be

configured to meet the voltage and power required to evaluate the device under test for devices under 50kW.

The laboratory evaluations on utility-interconnected PV inverters are categorized in two distinct performance characteristics: 1) utility compatibility evaluations, and 2) inverter power quality and PV utilization/optimization evaluations. The utility compatibility evaluations can be accomplished by using a power supply and placing the device under test in a constant voltage mode and following evaluations described in IEEE 1547[1]. For the PV array utilization evaluations, the tests are accomplished using the PV array mentioned above and a DayStar IV curve tracer that allows us to measure the key PV array operating parameters: Voc, Isc, Vmp, Imp, and Pmp. These parameters that can be entered into the PV simulator and will adjust the IV curve accordingly.

These same parameters are used as part of the PV simulator validation tests and are implemented to evaluate the inverter's performance when connected to PV versus while connected to the PV simulator. To demonstrate the effectiveness of the simulator to deliver PV power comparable to the actual PV array, a series of tests have been performed that characterize an inverter's operation with the PV array and then with the PV simulator. The validation tests were conducted with an inverter that has been known to have a less-than-optimal MPPT algorithm.

To monitor the operation of the inverter while powered from both sources, the inverter is instrumented and connected to the DC source and the utility as shown in Figure 4. The one-line diagram details the DC and AC interconnection as well as the placement of the monitoring transducers.

Grid-Tied PV Inverter Configuration
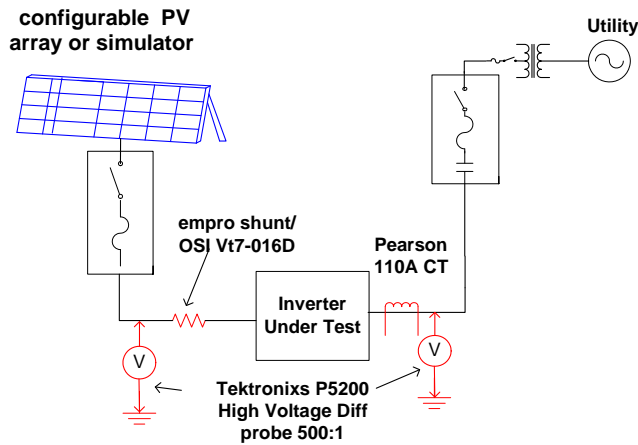
Fig. 4: Utility-interconnected PV inverter diagram

A LabView data acquisitions system (DAS) has been programmed to determine power quality values and power conversion efficiency values. The DAC captures the transducers' signals and calculates the inverter's DC and AC power. Since the inverter's performance will be evaluated using two different inputs, a fast data acquisition rate is desired. For these tests the DAS is capturing data every second; therefore, the ability to capture the inverter's response to irradiance variations is adequate.

The irradiance is key in evaluating the performance of the inverter while connected to both DC sources, so a fast sampling irradiance measurement is essential for both clear day (steady-state) and cloudy (dynamic) conditions. At the DETL, a five-node irradiance monitoring system exists that provides global and plane of array irradiance measurements. These measurements are used to provide a playback comparison on the performance of the inverter when connected to both DC sources.

TEST RESULTS

The inverter was connected to a PV array and the utility as shown in the drawing in Figure 4. The first test conducted on the inverter was a full-day operation test with several interruptions in operation to capture the inverter's startup routine. The PV array consisted of three parallel strings, with each string having 10 series-connected Solar World SW175 modules.

The PV simulator is programmed with the same DC parameters as the Solar World PV module and is configured to deliver the same voltage and power level as the PV array - three parallel strings, with each string having 10 series-connected modules. Demonstrating the effectiveness of the simulator to deliver PV power comparable to the actual PV array was accomplished by conducting similar and repeatable tests on the inverter and characterizing the inverter's operation with the PV array and with the PV simulator. These evaluations involve dynamic irradiance condition operation and the inverter's response during startup operation after the disruption of operation.

An inverter with known MPPT issues was chosen for this evaluation. The most significant MPPT issues arise when the utility has been removed and the inverter has to restart, or when the DC has been removed and the inverter has to restart. During these occurrences the inverter recovers slowly, and the opportunity to compare the response when powered with PV versus when powered with the simulator provides a good data point as to how representative the PV simulator is to actual PV. Figure 5 shows the result of the inverter re-starting after a shutdown due to the removal of the utility. There is a difference in response on the inverter, but it isn't significant and is associated more with the turning on of the inverter with the different sources that may be associated with the data acquisition timing. The AC power curve and the ripple associated with the operation is indicative of comparable operation. The DC voltages are slightly different during open circuit voltage and diverge slightly more due to the different power points but converge as AC power converges.
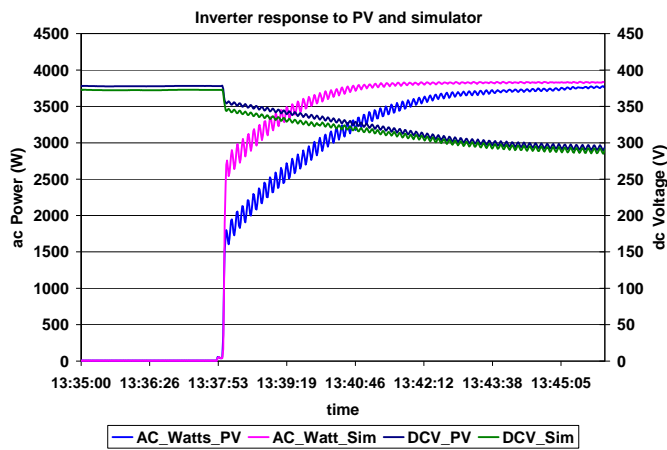
Fig. 5: Inverter response to utility disconnect when powered by PV and by PV simulator

Another function of the PV simulator is to provide an active window showing the PV array IV curve and the maximum power point on the curve. It also displays where the inverter is operating. Figure 6 shows the IV curve for the PV configuration, the maximum power point, and the inverter maximum power point. During low irradiance this inverter is off the point as noted in Figure 6.
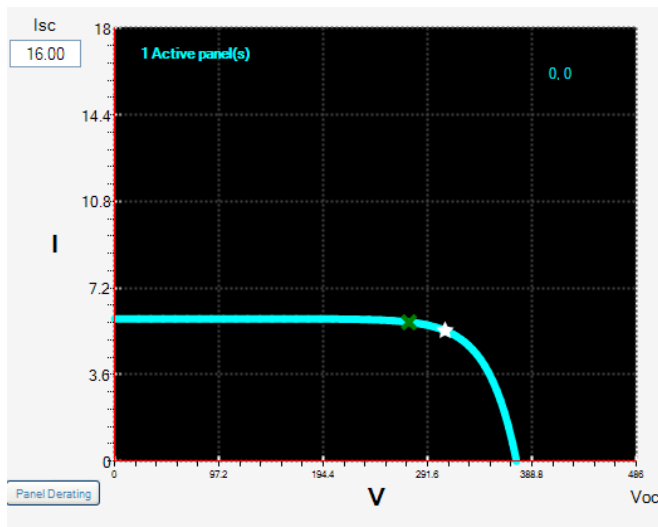
Fig. 6: PV simulator calculated maximum power point and inverter's operating maximum power point

FUTURE TEST

More performance evaluations are needed to fully validate the performance of PV inverters when the DC power is supplied by the PV simulator. As more irradiance and module temperature data becomes available, the information will be modeled using a Photovoltaic Array

Performance Model[2] along with the measured data from actual PV and will be compared to the PV simulator's output. This will be done with both steady-state and dynamic irradiance conditions.

SUMMARY

Validating the energy harvest performance of PV inverters and performing utility performance evaluations on a PV inverter are best accomplished with a source that can reproduce the input conditions. This allows adjustments to be made and the evaluation process to be repeated to optimize the MPPT algorithms. This fully-integrated PV simulator from AMETEK has performed well in preliminary evaluations and has shown the flexibility necessary to exercise the variations in MPPT algorithms. The multi-port design enables multi-MPPT input inverters to be assessed and validates the functionality and capability of these devices to utilize different types of PV technologies and sized arrays.

ACKNOWLEDGMENTS

REFERENCES

[1] IEEE 1547 Std 1547-2003, *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems,* Institute of Electrical and Electronics Engineers, Inc., New York, NY.

[2] D. L. King et al., "Photovoltaic Array Performance Model," Sandia internal document SAND 2004-3535.